The THz topics generated keen interests with more and more exciting applications including high data rate THz communication, pollutant sensing and analysis, non-invasive imaging, and non-destructive inspection to cite a few. The fundamental research activities crucial for the development of new concepts will also be addressed and include topics such as, efficiency of THz emitters and detectors, or new passive components.

The ambition of this conference is to bring together the various international (European) players in the THz domain including academics, industrials and public partners. The participation of students and young scientists is strongly encouraged with special rates. Some key topics dedicated to the Mid and Far Infrared domain will be also encompassed in the program.

Topics of the “9th THz Days” joined to the annual meeting of the GDR Nano Tera Mir include (but are not limited to):

- Sources, Detectors, and Receiver
- Spectroscopy of Gases, Liquids, and Solids
- Devices, Components, and Systems
- Frequency and Time Domain Instruments
- MMW and Sub-millimeter Wave Radar and Communications
- Imaging
- Mid Infrared Technology
- Applications in Biology and Medicine
- Applications in Security and Defense
- Metrology
- High-Field THz Wave Generation and Nonlinear THz Physics
- Far Infrared / IR Components and Systems
- Applications in Industry

Conference co-chairs

Gaël MOURET
(LPCA, Univ. Littoral Côte d’Opale, France)

Jean-François LAMPIN
(IEMN, Université de Lille 1, Lille, France)
Program

12H00 : Welcome / registration

13H30 : Opening
Brief information (C. Sirtori, J. Mangeney)

14H00 : Session 1 - Sources (THz and MIR)
Chairman : T. Yasui

14H00 : M1 - S. Houver
«Multi-THz Sideband Generation on an optical telecom carrier at room temperature»

14H30 : M2 - F. Joint
«Development of low power consumption quantum cascade lasers at 2.7 THz for compact and ultra-sensitive heterodyne detectors»

14H45 : M3 - S. Barbieri
«5ps-long terahertz pulses from an active mode-locked quantum cascade laser»

15H00 : M4 - R. Wang
«DFB laser array in the 2.3 μm wavelength range on a silicon photonic integrated circuit»

15H15 : M5 - K. Maussang
«Monolithic Echo-less Photoconductive Switches for High-Resolution Terahertz Time-domain Spectroscopy»

15H30 : *** Coffee break ***
Multi-THz Sideband Generation on an optical telecom carrier at room temperature

S. Houver1, A. Lebreton1, A. Mottaghizadeh2, M. I. Amanti2, C. Sirtot2, G. Beaudoin3, I. Sagnes3, O. Parillaud4, R. Colombelli3, J. Tignon1 and S. S. Dhillon1

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Wavelength shifting is an important process in fiber-optical communications, and is implicated for example, for transferring information between low-loss transmission windows, typically between 1.3 µm and 1.55 µm. This is normally achieved using optical-electrical-optical (OEO) switches that results in speed bottlenecks. Here, we demonstrate an all-optical wavelength shifting scheme using quantum cascade lasers (QCLs) [1] for the generation of sidebands on an optical telecom carrier at room temperature, potentially being considerably faster than OEOs. The process is based on resonant nonlinearities where phase matching is less critical. This work is the first demonstration of telecom sideband generation at room temperature with QCLs, where previous works with QCLs [2-4] have been limited to optical pumps in the near-infrared range (~800 nm).

The wavelength shift in the telecom domain was achieved by nonlinear sideband generation using a modified MIR QCL (λ=10μm, E_QCL), based on InGaAs/AlInAs quantum wells on an InP substrate, and a resonant telecom pump, E_telecom. The scheme (shown in fig. 1), permits the generation of sidebands at E_telecom ± E_QCL, translating into wavelength shifts over the entire telecom band, from 1300 nm to 1700 nm. The telecom pump and sideband are separated by 140 meV (i.e. the QCL photon) corresponding to Δλ~250 nm in the telecom range, permitting to shift from 1.3 µm to 1.55 µm and vice-versa. Demonstrations at room temperature are shown. THz sideband generation with InGaAs/AlInAs THz QCLs are also demonstrated and compared to those in the MIR (both sum frequency generation (SFG) shown on fig. 2). This is correlated with nonlinear susceptibility calculations highlighting the contribution of the interband and intersubband transitions to the nonlinear efficiency.

To conclude, sideband generation in the telecom range has been demonstrated at room temperature. This demonstration in the telecom range will further permit novel approaches for the QCL stabilization and the up-conversion of the MIR emission to the telecom domain.

Figure 1: Schematic of the telecom nonlinear frequency mixing in a QCL

Figure 2: Spectrum showing THz SFG at E_telecom+E_THz (green) and MIR SFG at E_telecom+E_MIR (blue)

Development of low power consumption quantum cascade lasers at 2.7 THz for compact and ultra-sensitive heterodyne detectors

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There is a particular interest in astronomy for the detection of radiation emission from cold interstellar gases. These emissions typically fall in the THz range of the electromagnetic spectrum: for instance, an important transition of deuterated hydrogen falls at 2.7 THz (90 cm⁻¹). Heterodyne detection is ideally suited to capture these weak signals.

Heterodyne detection requires local oscillator sources that operate a few GHz away from the frequency of interest. THz quantum cascade lasers (QCL) emerge therefore as suitable sources for the detection of signals above 2 THz. The combination of a THz QCL with an ultra-sensitive hot electron bolometer (HEB) cooled at 4K for the mixing is an optimal setup configuration.

The first building-block of our system is a single mode emission, low power consumption THz QCL operating at a specified target frequency. The Fabry-Pérot THz QCL is of limited use since its output power is distributed over many spectral modes. The approach we have chosen is the distributed-feedback (DFB) architecture, in particular the 3rd-order DFB approach that can provide single mode emission as well as small beam divergence. The DFB is implemented by introducing a deeply-etched lateral corrugation along the laser ridge that provides the necessary distributed feedback.

To obtain single mode operation at the desired frequency we have fabricated several devices with different grating periods and/or grating duty cycle. This strategy permits to finely cover a relatively broad range of emission frequencies. Upon electro-optical characterization of the lasers, the devices that best suit the application can be selected. The laser implementation is based on judicious electromagnetic modeling. In particular, care have been taken in order to reduce the overall size as much as possible, in order to minimize the power dissipation. We obtained devices with total dissipation inferior to 100 mW, a value compatible with HEB integration.

Finally, we have developed a system based on a Pirex dielectric hollow waveguide to re-shape the QCL output beam into a Gaussian beam, as well behaved far-field patterns are required for efficient coupling with the HEB. This approach also improves the simplicity of the quasi-optical coupling and alignment with the mixer.

5ps-long terahertz pulses from an active mode-locked quantum cascade laser

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We report the active mode-locking of a 2.5THz Quantum Cascade Laser (QCL) emitting in free running over a bandwidth of ~300GHz\cite{1}. The QCL was driven in mode-locking regime by modulating its current at the cavity roundtrip frequency with a low power Radio-Frequency (RF) wave. Therefore the effect of the RF modulation is solely that of mutually locking the phases of the existing modes, without affecting the modes amplitudes. This is in striking contrast with previous reports of active mode-locking where multimode emission was the direct consequence of the RF modulation\cite{2,3}. As shown in the Figure, by measuring the THz electric field amplitude vs time we find a double-pulse structure at twice the cavity free-spectral range. The emitted pulses are transform-limited, with durations of ~6ps and ~5ps respectively, the shortest achieved to date with active mode-locked THz QCLs\cite{1,2,3}. Such short pulses were obtained thanks to the use of a metal-metal waveguide, which favors lasing over a broader spectral bandwidth compared to previously employed single-plasmon waveguides.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Electro-optically sampled pulse train emitted by the actively mode-locked QCL (normalised intensity).}
\end{figure}

References
DFB laser array in the 2.3 µm wavelength range on a silicon photonic integrated circuit

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The spectral range of 2.3 µm is of interest for gas sensing as many important gases have strong absorption lines in this wavelength range, including NH\(_3\), CH\(_4\), CO, C\(_2\)H\(_2\) and HF. Besides, it also attracts interest in bio-sensing applications, such as non-invasive blood glucose measurements. Recently developed short-wave infrared and mid-infrared silicon photonic integrated circuits offer great potential to realize miniature gas and bio-sensors on silicon photonics chips. Low-loss and compact mid-infrared circuits can be fabricated in a CMOS pilot line, which enables high performance passive components such as (de)multiplexer. A compact silicon photonics spectroscopic sensor requires an integrated light source on silicon. However, the development of silicon photonics light sources above 2 µm wavelength still lags behind.

![Fig.1. Heterogeneously integrated 2.3 µm III-V-on-silicon DFB lasers with different silicon grating pitches (a) and device widths (b) in an array.](image)

At Ghent University-IMEC, we developed a heterogeneous III-V-on-silicon platform for optical communication and sensing applications [1]. Here we report 2.3 µm range InP-based type-II DFB laser arrays heterogeneously integrated on a silicon photonic integrated circuit (PIC). An InP-based type-II epitaxial layer stack with “W”-shaped InGaAs/GaAsSb quantum wells is used as the gain medium and bonded to the silicon PIC. Detailed information of the device structure and fabrication process flow can be found in [2]. As shown in Fig. 1(a), the continuous wave (CW) operated DFB lasers can cover a broad wavelength range from 2.28 µm to 2.43 µm by varying the silicon grating pitch. By adjusting the laser device widths, a four wavelength DFB laser array with 10 nm continuous tuning is achieved as shown Fig. 1(b). In CW regime, the DFB laser can operate up to 25 °C and emits a maximum optical power of around 3 mW at 5 °C.

References
Monolithic Echo-less Photoconductive Switches for High-Resolution Terahertz Time-domain Spectroscopy


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Interdigitated photoconductive (iPC) switches are powerful and convenient devices for time-resolved spectroscopy, with the ability to operate both as sources and detectors of terahertz (THz) frequency pulses. However, reflection of the emitted or detected radiation within the device substrate can lead to echoes that inherently limits the spectroscopic resolution achievable from their use in time-domain spectroscopy (TDS) systems. For example, with a photoconductive switch made from a 500 µm thick GaAs wafer and with \( n = 3.6 \) in the THz range, the first THz echo arises after only 12 ps, limiting the resolution to \(~ 90 \) GHz \((3 \text{ cm}^{-1})\). This can restrict applications such as high resolution THz spectroscopy of many polar molecules, where pure rotational spectra typically have linewidths ranging from 0.1 cm\(^{-1}\) to 10 cm\(^{-1}\).

A novel iPC switch that suppresses unwanted echoes from the substrate, without power losses, is proposed and demonstrated in emission [1] and in detection [2]. It provides a monolithic “on-chip” solution without any mechanical positioning of external elements post processing. For emitter, this is realized through a buried metal geometry where a metal plane is placed at a subwavelength thickness below the surface switch structure and semi-insulating GaAs active layer. For detector, this is realized through a buried multilayer low-temperature-grown GaAs (LT-GaAs) structure that retains its ultrafast properties, which after wafer bonding to a metal-coated host substrate, results in an iPC switch with a metal plane buried at a subwavelength depth below the LT-GaAs surface (see Fig.1). Using these devices as emitter and detector together enables echo-free THz-TDS and high-resolution spectroscopy, with a resolution limited only by the temporal length of the measurement governed by the mechanical delay line used. Rotational lines of water have been resolved as a proof-of-principle.

References

Figure: Top: Buried metal geometry for echo-less detection with LT-GaAs active layer. Bottom: Temporal scan of buried metal IPC and standard antenna
16H00 : **Session 2 - Detectors**

*Chairman : M. Huber*

16H00 : **M6** - A. Kuzmin  
«Ultra-fast Superconducting THz Detectors based on YBCO and Niobium Nitride»

16H30 : **M7** - C. Abadie  
«Development of tunable THz quantum well photodetectors»

16H45 : **M8** - M. Billet  
«Heterodyne detection of sub-THz waves using LT-GaAs photoconductor controlled by a wavelength of 1550 nm»

17H00 : **M9** - F. Simoens  
«Uncooled Terahertz real-time imaging sensors developed at LETI: present status and perspectives»

17H15 : **M10** - A. Lisauskas  
«High-performance THz detectors in 90 nm Si CMOS technology»

17H30 : **M11** - L. Mavarani  
«A silicon-based terahertz near-field imaging sensor for ex vivo life-science applications»

17H15 : *** Poster session along with tasting of local beers ***

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Ultra-fast Superconducting THz Detectors based on YBCO and Niobium Nitride

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Terahertz detectors based on the high-temperature superconductor YBa²Cu₃O₇₋ₓ (YBCO) and on ultra-thin niobium nitride (NbN) offer both a high sensitivity and a fast response time. For direct THz detection response times of 16 ps (FWHM) for YBCO and 150 ps for NbN have been demonstrated [1], [2]. A sub-gap THz response relies on the vortex-assisted mechanisms [3]. Detectors work as hot-electron bolometers for the photon energies, which are larger than superconducting gap. The NbN hot-electron bolometers have a significantly higher sensitivity and proofed to be working in high THz region but they are approximately 10 times slower and require 4-K operation temperatures.

An important application, where such unprecedented speed and sensitivity are required, is the single-shot analysis of THz pulses of high repletion rates ($10^8$ – $10^9$ Hz), generated by the electron synchrotrons. In the so-called low-α mode of operation, when the electron bunch length is shorter than the wavelength, the Coherent Synchrotron Radiation (CSR) of very high brilliance is possible. It results in few ps-long, high-intensity, few-cycle electromagnetic pulses. The spectrum of these pulses lies mainly in the 0.1 – 1 THz range. Due to electron-bunch instabilities the characteristics of every pulse could vary due to bursting effect [4]. In order to understand and control this phenomenon one would need to analyse every pulse individually. Low-resolution spectroscopy at few frequency points could shed a light on bursting effects. We present results of our efforts to build frequency selective few-pixel arrays of the ultra-fast YBCO and NbN detectors for the analysis of THz CSR.

References
Development of tunable THz quantum well photodetectors

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Developing devices (detectors, emitters) operating in the THz range is important because of perspective applications in metrology, healthcare, process control as many organic molecules absorb in this spectral range. As far as detection is concerned, most of the currently available detectors are thermal devices that have slow response times.

Our goal here is to develop AlGaAs/GaAs quantum well infrared photo-detectors (QWIP) with a resonant frequency around 3 THz (≈100µm) by using a 3D split ring resonator (SRR) inspired geometry (Figure 1). The micro-resonator is electrically an RLC circuit as depicted in Figure 1(b). It has been proven that, by changing the length of the antenna (inductive component of the circuit), the resonant wavelength tunes in the 100-300 µm range [1]. To implement an active device based on this architecture we need to overcome the problem that this 3D SRR is intrinsically a short-circuited system. A possible solution, implemented in [2], is the etching of the gold ground plane to enable the electrical injection through the active region.

In the new approach presented in this contribution, we assure the current flow in the active region by separating the two contacts with a 300nm-thick Si\(_3\)N\(_4\) layer. Through finite elements numerical simulations, we are able to model and predict the electromagnetic behavior of the structure. The fabricated devices (SEM image in Figure 1 (c)) were first electrically characterized at room temperature. A single device ("pixel") has a resistance in the range of 1-10MΩ while the 5x5 array has a typical measured resistance of the order of 100kΩ. Further tests on the Si\(_3\)N\(_4\) insulating layer are currently being made to improve both the electrical and mechanical robustness.

![Diagram of the new contact design](image1)

**Fig. 1.** (a) Scheme of the new contact design. (b) Equivalent electrical circuit of the device. (c) SEM image of the fabricated sample.

Heterodyne detection of sub-THz waves using LT-GaAs photoconductor controlled by a wavelength of 1550 nm

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The low-temperature-grown GaAs (LT-GaAs) is a suitable photoconductive material for THz optoelectronics devices because of its excellent electrical properties after post-growth annealing such as high dark resistivity, high free carrier mobility, and short free carriers lifetime ($\tau<1$ ps) [1]. Recently, it has been shown that an efficient LT-GaAs photoconductor operating at $\lambda=1550$ nm can be obtained by placing the LT-GaAs layer inside an optical resonant cavity [2]. We present here a photoconductor composed by a thin and small area LT-GaAs layer with a thickness $t=450$ nm and a diameter $D=6$ µm, placed between two gold mirrors/electrodes. The top face electrode is a nanostructured grating of gold with a sub-wavelength periodicity $p=900$ nm, an aperture $a=300$ nm and a thickness $h=300$ nm. The device is shown in figure 1. RF waves at a frequency of $f_{in}=67$ GHz generated by a microwave synthesizer are send to the LT-GaAs photodetector through a first 50-Ω-microstrip line using a coplanar probe. At the same time the photoconductor is triggered by a 1550 nm optical pulse train produced by a mode-locked fs laser, giving rise to a conductivity comb with a teeth spacing equal to $f_{rep}=1$ GHz. At the photomixer output the beating of the RF wave with the comb teeth generates replicas spaced by $f_{rep}$. We are interested here in the base band replica which is below $f_{rep}/2$. This mixing signal is outcoupled by another coplanar probe through a second microstrip line and sent through a bias-T to a spectrum analyser. Figure 2 shows the detected signal power ($P_s$) for an input RF frequency at 67 GHz for different input power levels $P_in$ and different optical powers $P_opt$. The conversion losses $L=10\times\log (P_{in}/P_s)$ between the probes, are equal to 84 dB for $P_{opt}=11.8$ mW and 54 dB for $P_{opt}=88.2$ mW and are independent of the input power $P_{in}$. These results show the possibility to detect RF and THz waves by photoconductive sampling using LT-GaAs under 1550 nm illumination.

This work is supported by the Direction Générale de l’Armement, RENATECH network and Université des sciences et technologies de Lille. We gratefully acknowledge Christophe Coinon and Xavier Wallart for the epitaxial growth of the LT-GaAs layer.

Uncooled Terahertz real-time imaging sensors developed at LETI: present status and perspectives
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The commercial spread of terahertz (THz) cameras has to fulfill simultaneously the criteria of high sensitivity and low cost and SWAP (size, weight and power). Monolithic silicon-based 2D sensors integrated in uncooled THz real-time cameras are good candidates to meet these requirements. Over the past decade, LETI has been studying and developing such arrays with two complimentary technological approaches, i.e. antenna-coupled silicon bolometers and CMOS Field Effect Transistors (FET), both being compatible to standard silicon microelectronics processes.

LETI has built upon its know-how in thermal infrared bolometer sensors a proprietary architecture for THz sensing. High technological maturity has been achieved as illustrated by the demonstration of fast scanning of large field of view and the recent birth of a commercial camera in collaboration with the French SME I2S.

Two FET-based approaches are developed at LETI: direct detection and heterodyne detection. The former technic has reached the most advanced demonstration with 31x31 arrays and real-time 2D imaging, while the latter has been demonstrated with single-point heterodyne detector and raster scanning and showed very promising sensitivity.

The authors describe the present status of these developments and perspectives of performance evolutions are discussed.

References
This paper discusses important aspects of physics-based circuit modelling and design of high-performance field-effect-transistor based terahertz detectors (TeraFETs). TeraFET power detection is based on rectification of THz waves coupled into the channel of a FET. Whereas, at low frequencies, FET-based rectifiers rely on resistive mixing, with rising frequency, charge-density waves in the channel play an increasingly important role and enable detection and mixing far beyond classical cut-off frequencies [1, 2]. The potential of convenient fabrication of TeraFETs by Si CMOS foundry technologies has accelerated developments, which have already led to implementation of real-time camera [2, 3], while detector optimization is still ongoing, gradually leading up to fundamental performance limits for room-temperature operation of the devices.

We have developed a circuit model allowing to evaluate the role of the transistor geometry parameters such as channel length and width taking into account antenna impedance matching and the peculiarities of fabrication technology. Whereas the highest sensitivity is reachable for the shortest, technology defined, gate lengths, there is an optimum value for a gate width. In support of our arguments, we present implementations of several types of narrow-band and broadband detectors using a 90-nm CMOS technology (see micrographs in Fig. 1). At 630 GHz resonant frequency, narrow-band devices reach optical responsivity of 1074 V/W and NEP of 10 pW/√Hz. From 500 GHz to 650 GHz a broad-band bow-tie antenna and hyper-hemispheric lens coupled TeraFETs demonstrate flat device responsivity (taking all available beam power) of 100 V/W with NEP of 75 pW/√Hz.

References
A silicon-based terahertz near-field imaging sensor for ex vivo life-science applications

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This work shows the advances in the development of a silicon-based terahertz (THz) sub-wavelength imager for tumour margin identification. A fully integrated 0.55 THz near-field sensor implemented in 0.13 µm SiGe HBT technology has been successfully developed [1] and modified [2] by applying a chopping technique resulting in highly improved signal-to-noise-ratio (SNR) (Fig.1). Other than presently available systems based on scanning near-field optical microscopy (SNOM) this sensor could be a possibility to tackle problems like long integration times and sensitivity limitations in these systems [3]. In parallel, using THz Time-Domain-Spectroscopy (TDS) fresh and fixed tissue sections were measured to detect the best suited frequencies for tumour detection. The knowledge of these frequencies combined with the single-pixel near-field sensor could be used for the development of a multi-pixel near-field imager for life-science applications [4].

![Fig.1. Signal-to-noise ratio of the chopped near-field sensor signal](image)

Funding: This work is part of the project "NearSense- A silicon-based terahertz near-field imaging array for ex vivo life-science applications" and was funded in the frame of the DFG priority program SPP 1857 "ESSENCE" ("Elektromagnetic Sensors for Life Sciences").

References
Poster Session
Evolutionary Algorithm-Based Analysis Of The Rovibrational SCl₂ Stretching Bands Of Thionyl Chloride

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Thionyl chloride (SOCl₂) is a volatile inorganic compound extensively used in the industry and whose monitoring in the gas phase is critical both from environmental and military concerns. Pure rotational and rovibrational spectra of SOCl₂ and several of its isotopologues, were characterized recently in the microwave, submillimeter, and far-infrared spectral regions [1] [2]. The rotationally resolved vibrational spectra of the SOCl₂ asymmetric \( \nu_5 \) (459 cm\(^{-1}\)) and symmetric \( \nu_2 \) (500 cm\(^{-1}\)) SCl₂ stretching fundamental bands have been measured by means of high resolution (R = 0.001 cm\(^{-1}\)) FT-FIR spectroscopy on the AILES beamline of the SOLEIL synchrotron facility. These two bands overlap with a strong SO₂ band (520 cm\(^{-1}\)) arising from the very efficient hydrolysis of SOCl₂ with residual traces of water [3].

Evolutionary algorithms implemented in the automated fit programs developed by the Nijmegen and Düsseldorf groups [4] have enabled the analysis of the \( \nu_5 \) and \( \nu_2 \) bands of two isotopologues (\(^{32}\)S\(^{16}\)O\(^{35}\)Cl₂ and \(^{32}\)S\(^{16}\)O\(^{37}\)Cl₂), despite the presence of the SO₂ band and thus demonstrating the power of evolutionary algorithms applied to the spectroscopic analysis of congested spectra. This work helped to identify the pure rotational structure of the \( \nu_2=1 \) and \( \nu_5=1 \) vibrational states of \(^{32}\)S\(^{16}\)O\(^{35}\)Cl₂ in the submillimeter spectrum of Ref[2], as well as the \( \nu_2=1 \) state (not-active in the FIR region). A global fit gathering all the microwave, submillimeter and Far-IR data of thionyl chloride has been performed. Almost all reachable excited rovibrational energy levels have been included in assigned transitions suggesting that no effective interaction was observed.

References
The use of the sub-mm/Terahertz (SMM/THz) band (0.1 to 10 THz) for the analysis of gas phase systems is attractive due to a vast number of light polar compounds which produce strong rotational spectra. In particular, at low pressure, the molecular linewidths approach the Doppler limit and the narrowness of the spectral features ensures that an excellent selectivity can be achieved even in complex mixtures. In order to exploit these features considerable attention has been paid to the technological development of radiation sources able to operate in this regime. At present, only amplified multiplier chains (AMC) and photomixer (PM) sources are practicable when high-resolution spectra are required for the analysis and quantification of gas phase species.

A new technique employing a MW Chirped-Pulse (CP) has recently been developed (Dian et al. 2008). A coherent emission is produced by the sample, a process termed Free Inductive Decay (FID). The FID can be recorded after the end of the excitation pulse overcoming the difficulties of the absorption configuration. The intensity of the FID decays as the sample gradually dephases and returns to its unpolarised state. Powerful MW solid state or traveling wave tube amplifiers are now available enabling the development of faster techniques such as CP spectroscopy where no mechanical scanning is required. The strategy employed in this case is to record the phase coherent FID with the largest possible bandwidth, the signal to noise ratio is optimised by temporal accumulation. This has the advantage of being a multiplex approach, by recording the time dependent FID and taking the Fast Fourier Transform (FFT), the entire instrument bandwidth is obtained simultaneously.

A chirped Pulse sub-millimetre (CP-SMM) spectrometer as been developed in Dunkirk in the 190-210 GHz region. Experimental setup will be described with its optimization for spectroscopy research or molecular detection.

Reference:
GaN distributed transferred electron device based THz oscillator modeling

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The realization of useful solid state THz power sources is still today a challenge. Among the possible electronic and optic solutions is the gallium nitride (GaN) transferred electron device. Some theoretical and experimental research works have concerned vertical lumped structures but none distributed ones which structure is similar to a microstrip line or a N⁺N⁺ multilayer parallel waveguide in the case of a bidimensional (2D) theoretical approach (figure 1). Its RF operation is based on the interaction between an electromagnetic wave propagating along the device epitaxial layers and electrons moving perpendicularly which RF operation is the accumulation layer and transit time mode. The wave amplification is obtained in the N active zone behaving as a negative resistance medium. The oscillator complex RF operation is modelled by means of a 2D time-domain physical simulator based on the self-consistent solution of both the Maxwell and energy-momentum macroscopic electron transport equations. Thus, space-time physical and functional quantity analysis can be performed following electromagnetic and quasi-electrostatic approaches [1]. The semiconductor structure is preliminary optimized to operate at 1 THz.

Simulations start from a DC solution and described the transient and continous wave operation. Figure 2, as an exemple, illustrates the transient evolution of the terms constituting the energy conservation equation. Figure 3 shows the frequency spectrum of the net electromagnetic (EM) power under CW operation. The main line is 1 THz. This result is consistent with the expected oscillator DC and RF operation and semiconductor structure design.

References
Dielectric metamaterial-based gradient index lens in the terahertz frequency range

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We have tailored the effective refractive index of dielectric metamaterials to design a flat lens operating at terahertz frequencies. The studied dielectric metamaterials consist of high permittivity resonators, whose first Mie resonance gives rise to resonant effective permeability. The resonance frequency is fixed by the size of the resonators. By varying this size, we could adjust the value of the resonance of the effective permittivity and, thereby, of the effective refractive index. Then, we fitted this one to the profile of refractive index of a graded index flat lens, of which we show that it focuses an incident plane wave at terahertz frequencies and that the spot in the focal plane is diffraction-limited. It is less than one and a half wavelength thick, its focal length is only a few wavelengths. Thus, we show that dielectric metamaterials are suitable for the design of metadevices, that is, photonic components for applications at terahertz frequencies.

Index Terms—Gradient-index lenses, Metamaterials, Resonators, Terahertz imaging, Dielectric materials.

Fig. 1. Map of the EM field intensity (time-average of the square of the EM field (\(H_z^2\))) of an incident TE plane wave at 0.3THz on the flat lens ((x,y) plane as in fig. 3). The flat lens consists of a ten layers DMM constituted of square cross section high permittivity cylinders which sustain Mie resonances. Their length size is varying perpendicularly to the direction of propagation from 70\(\mu\)m at the center to 57\(\mu\)m at the edges. The two vertical green lines delimit the lens. The simulated focal length is \(\approx 5\lambda\).

References

LIGA micro-fabrication of THz components


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LIGA (German acronym for Lithography, Electroplating, Moulding) is a key technology for the micro-fabrication of High Aspect Ratio Micro Structures. Structures with heights of a few tens micrometers to a few millimetres with high aspect ratio are fabricated in a wide range of materials like polymers, metals and ceramics. These structures can be made of complex shapes with a sub-micrometer lateral resolution. This technology relies on synchrotron radiation to provide extreme precision and depth of field. LIGA technology at laboratory SOLEIL allowed some accomplishments in THz domain as Slow Wave Structure (fig.1) [1] and multiplexers [2]. Metamaterials (MM) due to their unique possibility of structural design are suitable materials to construct optical devices operating in the THz range with unusual properties as left handed behavior, negative refraction and sub-wavelength focusing. With their potential low losses and isotropic properties, ADMs are considered as an improvement against metallic MMs. Within the TeraMetaDiel project*, partners intended to design, to fabricate and to characterize All-Dielectric Metamaterials (ADM) which rely on Mie resonances of high permittivity ceramic resonators in the THz range. SrTiO3 were synthesized as powders and shaped, LIGA technology provided micro-structured tools in order to perform ultrasonic manufacturing to fit a specific gradient in order to ensure the requisite resonances.

Fig.1. Slow Wave Structure (THz amplifier), copper structures height are 62+-2µm.

References

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Evaluation and correction of distortion for real-time terahertz camera

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Terahertz active imaging in transmission is an elegant solution to see through object made of non-polar materials optically opaque [1]. One of the main challenges of applied terahertz imaging is to achieve fast acquisition with high quality images. In particular, one has to take into account the geometrical aberrations of the optical set-up that generate image distortions. Distortions can be an important issue for advanced applications such as tomography [2].

In this study, we characterize the distortion of a real-time terahertz imaging set-up with the help of a hole array acting as a diffraction mask. The idea is to quantify experimentally the distortion and numerically correct images.

The THz source is the Teracascade QCL emitting 1mW at 2.5 THz [3]. The detector is the commercial TZcam camera from I2S society [4] that integrates the micro-bolometer array from CEA LETI (Fig. 1 (a)). The mask (Fig. 1 (b)) is 3D printed 3mm thick plate made in absorbing material. The array is composed of 2 mm and 3 mm diameter holes with a pitch of 4 mm. The external square is corresponding to the object field of view.

Fig. 1. (a) Terahertz imaging setup at 2.5 THz, (b) Optical picture of the mask holes, (c) Superposition of distorted mask image with the reference grid (d) Superposition of distortion corrected image with a new reference grid which matches all the points.

Terahertz normalized images in transmission of the mask is presented in Fig. 1 (c). The superposition of this image with a reference grid highlights the distortion due to geometrical aberrations of the complete optical set-up. The reference grid is created so that it matches the group of 4*4 holes at the center of the image. The paraxial magnification is equal 0.20 and the relative distortion calculated at edges positions is equal to 0.07.

To correct this pincushion distortion, a numerical algorithm is performed on the image with the calculated factor. The distortion corrected image is shown in Fig. 1 (d) where a new grid with a new paraxial magnification of 0.21 matches all the point of the mask.

References:
High-directivity terahertz TEM horn antenna based on Silicon
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In the terahertz range, the emission or detection of a signal uses generally planar antennas combined with silicon lenses. However, the planar antenna covers a wide area on the wafer and the positioning of the lens is fastidious. An alternative is the integrated TEM horn antenna (TEM-HA) that has been developed in our group [1]. In order to reduce the size of the chip and to combine the lens with the antenna, we have developed a new design of TEM-HA made on a high permittivity dielectric. This design is drawn from the description of the antenna as a micro-strip line [2] using its opening angles as parameters [3]. Thereafter, we used it to design a 50 Ω TEM-HA made with silicon. In addition, to reduce the internal reflections of the signal in the antenna, we added an anti-reflecting layer centered at 600 GHz. Simulations show 19 dBi of directivity (fig. 1) and a scattering parameter $S_{11}$ less than -10dB with a bandwidth of 150 GHz. Moreover, the antenna presents a very low dispersion for short pulses (fig. 2). Those promising simulations let us believe that further experiments will show usefulness of this antenna for wide bandwidth THz signals transmission.

Fig. 1 : Design and directivity of the TEM-HA at 600GHz
Fig. 2 : Pulse response of the TEM-HA

References:
Compound Eye Like Diffractive Optics for sub-THz camera

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The necessity of fast and efficient detection of THz radiation at room temperature is crucial in many applications concerning the fields such as medicine, security, quality inspection, aviation, military and many others. For selected application the critical parameter is spatial resolution in the captured image. For another group of applications critical parameters are extremely fast response and very wide angle of incidence. This last idea is realised in practise basing on the fast THz camera and sophisticated diffractive optics.

The Orteh Company designed and manufactured the standard matrix of 8x8 detectors based on field-effect transistors (FETs) with signal processed by fast FPGA circuits. The typical multiplexing technique is replaced by a parallel pixel processing. This innovative solution enables utilization of the separate lock-in for each pixel to enlarge the dynamics and sensitivity for the registered signal. For the static mode mentioned solution provides extremely fast image acquisition.

Additionally, we have designed dedicated matrix of lenses that focuses the incoming radiation on each detector and therefore strengthens the registered signal around 10 times [1]. Additionally matrix of lenses can significantly decrease an optical crosstalk. Such a matrix of lenses was designed for 0.3 THz and manufactured using 3D printing technique SLS (Selective Laser Sintering), which assures low attenuation and good physical parameters of the element.

Here, we would like to present a new type of the structure working together with THz Orteh camera – called a fly’s eye (sometimes also moth’s eye). This type of the structure was designed and dedicated for particular geometry of the designed matrix and allows for detection of THz radiation from much wider angle of incidence.

Fly’s eye-like diffractive structure together with THz camera with parallel processing provide features typical for insect vision – almost 180 deg. field of view and extremely fast response.

References
Sub-THz domain hybrid phase coding for large aperture lenses.

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For many THz application large aperture of the lens is necessary. The lightweight diffractive optics can provide low loss and better transparency than refractive one. The use of kinoform [1] phase coding is typically highly effective. However when large aperture lens are created with small focal length very strong shadow effect [2,3] appears on its edges. This effect can be significantly reduced by phase encoding with gradient index or in sub-wave technique. However, this method requires very large resolution or advanced technology. We propose coding the area that is vulnerable for shadow effect with binary phase. It will lower the shadow effect and increase the efficiency. With the simplicity of production it is a reasonable compromise.

In this article is presented hybrid diffractive structure consisting of phase encoded as a kinoform in the center and binary phase on the edges (fig.1.b). With this combination, for the lens aperture greater than the focal length, it is possible to considerably improve the performance in comparison to the structure coded entirely as a kinoform. All the modeling were provided for 288GHz frequency.

![Fig.1 Illustration of the possibility of eliminating the negative impact of shadow effect concept: a) kinoform with fast alternating phase on the edges of, b) hybrid structure consisting lens coded as kinoform in the middle and as binary structure on the edges.](image)

Computer modeling of designed structure efficiency and its comparison to other types of diffractive lenses for THz domain will be presented.

References

Spectroscopy of lasing lines of ammonia and deuterium oxide near 1 THz

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Optically pumped THz lasers (OPTL) with molecular gas as active medium are used for a long time[1]. For optical pumping of these lasers is usually used gas discharge laser (mostly CO₂ or N₂O) tuned in mid infrared spectral range. Because of this, OPTL are bulky and unpractical. Required coincidence between lines of pumping laser and THz active medium limits possible lasing lines and affect laser performance. With development of mid infrared quantum cascade lasers (MIR QCLs), which offer precise tunability and high power in wide spectral range, is possible to excite lines inaccessible by gas laser and obtain new THz lasing lines[2].

In our contribution we present spectroscopic measurements of ammonia (NH₃) and deuterium oxide (D₂O) lasing lines near 1 THz during optical pumping by MIR QCL. NH₃ spectra were obtained by frequency domain measurement employing THz multiplication chain and InSb hot electron bolometer. For measurement of D₂O lines was used vector network analyser applying time domain method. Measurements were performed at changing vapour pressures, different tunnings and powers of pumping MIR QLCs. Results show interesting gain values for measured lines which are perspective for construction of new powerful OPTLs.

Fig.1. Spectra of NH₃ line 1.073 THz optically pumped by MIR QCL tuned at slightly different frequencies. Measured in 50 cm long gas cell.

References
Compact THz nonreciprocal components using hexagonal ferrite ceramics

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A key element to protect coherent sources and achieve desired power stability and spectral purity for certain applications is an isolator, which in THz range has still no effective solution. Our concept of a novel THz isolating device builds on the recently demonstrated proof-of-principle design based on a one-way reflecting surface for NIR and visible wavelengths. This combines gyrotropy with a surface plasmon resonance [2]. A first crucial requirement to realize this, is a sufficiently strong THz gyrotropic material. In the last decade new fabrication and material processing methods have enabled a new type of ferrite material with hexagonal magnetoplumbite structure (e.g. SrFe12O19). Gyrotropy in this material is the result of gyromagnetic effects occurring when the saturation magnetization precesses nonreciprocally (NR) at Larmor frequency \( \omega_0 = \mu_0 \gamma H_{int} \) around internal magnetic field \( H_{int} \). As a result the permeability acquires a tensorial form and its unequal off-diagonal elements are responsible for NR behavior. The internal field in hexaferrites is particularly strong (up to 20kOe), resulting in a Larmor frequency in the mm-wave range.

A first important step for the development of the device is complete material characterization of the used hexaferrites. In a first instance the diagonal permittivity and permeability elements have been characterized using both standard Time-Domain Spectrometry (TDS) and time-windowed Vector Network Analyzer (VNA) characterization. In a second step, the off-diagonal tensorial contributions are characterized in a Faraday configuration by measuring the magnetized samples with magnetization co-aligned with the beam path. This was done both on the VNA setup and TDS (Fig. 1Left). The obtained strong THz gyrotropy of hexaferrites proves their unique potential for THz isolator applications, as will be shown by first designs of a NR magnetoplasmonic mirror using the fitted material parameters. Our design combines strong gyromagnetic properties of hexaferrites in THz range with surface plasmon resonances formed due to the presence of a metallic grating at the hexaferrite surface. Close to these SPP resonances there can appear frequency ranges where the device acts as a one-way mirror (Fig. 1Center). Figure 1Right shows first fabricated samples with 6 different filling factors of grating for test measurement.

Fig.1. Left: Difference in optical indices of hexaferrite for left and right circularly polarized light measured by TDS proving strong material gyrotropy. Center: simulation results showing a shift of reflection dip according the direction of substrate magnetization (or incidence). Right: Picture of the first fabricated samples for test measurement.

Separation of absorption and scattering contributions to the extinction coefficient of scattering samples in THz-TDS experiments

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**Context:** For experimental reason, some materials have to be diluted in a transparent hosting matrix (e.g. Polyethylene) to be characterized by terahertz time domain spectroscopy (THz-TDS). Therefore, the sample to be measured is a non-homogeneous pellet constituted of grains whose diameters \(\Phi\) could be as large as the THz wavelengths, leading to scattered transmitted THz waveform. In such condition, the extracted complex refractive index of powder materials in the THz range using THz-TDS suffers from both i) an overestimation of the absorption \(\alpha_{\text{TDS}}\) and a distortion of the spectral resonance peaks of the powder material [1], together with ii) a frequency-dependent distortion of the refractive index \(n_{\text{TDS}}\). Previous works [2] have pointed out and verified the scattering-induced distortion of both refractive index and absorption coefficient, according to exact Mie theory [3]. Some of them proposed numerical [4] and experimental [5] solutions to get rid of these scattering-induced effects in order to obtain the actual values of refractive index and absorption coefficient of the scattering sample. In this work, we propose a technique, which retrieves the actual optical constants \((n_0\) and \(\alpha_0)\) of a scattering sample by applying Kramers-Kronig transforms (KKT) to erroneous ones \((n_{\text{TDS}}\) and \(\alpha_{\text{TDS}}\)).

**Principle & preliminary results:** Since the \(n_{\text{TDS}}\) and \(\alpha_{\text{TDS}}\) of pellet-like samples are not impacted in the same manner by the presence of scatterers, the imaginary and real parts of the complex refractive index are not causally linked, as it should be. This results in a break of self-consistency of Kramers-Kronig relations. Nevertheless, by calculating \(n_{\text{KK}}\) and \(\alpha_{\text{KK}}\) from KKT of \(\alpha_{\text{TDS}}\) and \(n_{\text{TDS}}\), respectively, and by comparing each other, we show that the so-calculated optical constants are closer to the actual values. By repeating this process, \(n_{\text{KK}}\) and \(\alpha_{\text{KK}}\) converge to \(n_0\) and \(\alpha_0\), respectively. During the conference, authors will detail the technique and present works in progress.

![Extinction coefficient of fructose](image)

**Fig.1.** Extinction coefficient of fructose (blue curve) extracted from THz-TDS measurement of a 510-\(\mu\)m thick pellet constituted of fructose/HDPE mixture (70% mass concentration) having grain size 150\(\mu\)m\(<\Phi<200\mu\)m. The extinction coefficient corrected by our technique (red curve) tends to the theoretical values (dashed lines) predicted by Mie theory after 5 iterations.

**References**


Terahertz guided time domain reflectometry simulation for several waveguides and electronics packages

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Terahertz guided time domain reflectometry is a well-known technique allowing open circuit detection and localization in waveguides or 3D packages interconnections. It can be used to detect through silicon via (TSV) delamination [1], characterize open in solder bumps [2] and locate an open in a daisy chain [3] or a crack in a layer of an integrated circuit [4]. We used electromagnetic finite-difference time-domain method to simulate propagation and reflection of terahertz pulse in several components in order to evaluate order of magnitude of the signal that we can expect. We applied this method to millimeter-wave frequencies typical waveguides like coplanar, microstrip and single wire. We obtained in Fig 1 a signal reflected with a delay depending on the position of the defect. Then we applied this method to localization of open circuit in a BGA (ball grid array) package, a TSV and a daisy chain. We can see in Fig 1(d) and (e) that signal reflected depend on the connection between a BGA ball and the TSV.

Fig.1. (a) Waveguide with a defect (b) Signal reflection depending on the position of defect (c) Open between a BGA ball and a via (d) Signal reflected with open(e)Signal reflected when correctly connected

References :
Intersubband polaritons are mixed states, partially microcavity photon and partially material excitation. We demonstrate strong coupling between a THz intersubband transition and the fundamental cavity mode of a metal-insulator-metal resonator. Patterning of the resonator surface enables surface coupling of the radiation and introduces an energy dispersion which can be probed with angle-resolved reflectivity. Note: the polaritonic dispersion presents an accessible energy minimum at $k=0$. As a first approach, we have characterized the system at a fixed incidence angle of $15^\circ$ and at low temperature. We have found a minimum Rabi splitting of 16%, with a central frequency of 2.5 THz. The agreement between experiment and simulations is good, and it permits also to precisely gauge the exact doping of the semiconductor sample. The perspective of this work is to understand THz polariton’s scattering mechanisms. These mechanisms will be observed using a pump and probe experiment.

*Figure 1: Comparison between experimental absorption peaks (black dots) and dispersion simulations for different gratings on the same heterostructure at 2.5THz*
Abstract — We present a THz TDS study of different aged epoxy resin adhesive to investigate the potential of this technique for contact-free, non-destructive detection of ageing. The samples were aged artificially over 10 days and a conventional THz TDS system was used to evaluate their dielectric properties. Our results indicate that aged and unaged samples can be distinguished.

I. INTRODUCTION

The detection of aged adhesive material is of outmost importance for quality control of long-term used polymer materials. Especially epoxy resin adhesives represent an interesting material class as they are the basis of many modern adhered compounds [1]. The joint strength decreases under the influence of high temperature, UV radiation, or water. In order to detect aged materials, destructive mechanical tests are commonly used. In this study, we investigate cured plates of Polytec EP601-T epoxy resin adhesive, which are either thermally aged at 100°C UV irradiated or inserted into water each for one week. The samples were characterized with a standard fiber coupled THz-TDS system.

II. RESULTS

For data extraction the algorithm described in [2] was used. The differences in the absorption coefficient are negligibly small. Only the water aged samples show a higher absorption because of water embedment. However, the refractive index of the samples varies significantly. Figure 1 illustrates the frequency dependent refractive index of the differently aged epoxies. The refractive index of unaged polymers is about 1.55, whereas it increases during thermal aging. Here, post-cure and cross-link effects of the epoxy molecule may occur and the morphology changes. During the water immersion, the water molecules are embedded in the polymer matrix and therefore the refractive index increases, as previous studies suggested [3]. In opposite to the thermally aged samples, UV irradiation leads to a decrease in the refractive index allowing a distinction between the two ageing mechanisms. For a real application it is important to make a classification of the results, since the behavior slightly differs for different samples due to statistical fluctuations even if the same ageing mechanism is applied to the material. Therefore, a principle component analysis (PCA) of the frequency dependent refractive indices could be a more reliable method. Figure 2 shows the score plot of different aged samples, illustrated by their first two main components. It is possible to differentiate between three classes of aged (blue and red circles in fig. 2) and unaged (black circles) epoxies. However, it is yet not possible to distinguish thermal aged epoxies from water inserted, because in both cases the refractive index increases (see fig. 1).

III. SUMMARY

With THz TDS it is possible to characterize aged epoxy polymers nondestructively by comparing their refractive indices. A PCA could be a powerful tool to distinguish different aged epoxies. Further studies should focus on comparative measurements of mechanical tests and THz-TDS.

REFERENCES

Continuous-Wave Coherent and Tunable THz emission by photomixing driven by a dual-frequency external-cavity laser emitting at 1.064 µm: State-of-the art to potential applications

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The development of THz applications is presently mainly limited by the lack of flexible sources. Photo-mixing techniques are attractive for THz emission, since they rely on mature photonic components and offer straightforward broadband tunability. However, the scale factor between the laser frequencies (100’s of THz) and the beat frequency (THz) have a deleterious and significant impact on the THz signal in terms of output power and frequency noise that could be limiting for real applications. We recently proposed a robust dual-frequency vertical-external-cavity surface-emitting laser \([1]\) based on the simultaneous operation of two transverse modes within a single-cavity. More recently, we demonstrated coherent and tunable THz emission from this dual-frequency laser by excitation of a commercial uni-travelling-carrier photodiode \([2]\). As shown in the figure, the THz frequency noise is lower than the laser one for each transverse mode, thus validating the concept of this free-running dual-frequency laser.

![Frequency noise of the THz source versus dual-frequency source](image)

We will review the principle of operation of the dual-frequency laser and expose the state-of-the-art of the performances of the THz source, focusing on experimental techniques that offer a full characterization of the THz signal, such as output power, power spectral density and frequency noise. From these performances, we will discuss on two specific applications of this THz source, namely spectroscopy and imaging. We will propose possible schemes for spectroscopy applications based on the demonstrated 50–700-GHz 15-GHz-steps tunability and spectral coherence of the THz signal, along with perspectives on continuous tunability. We will also discuss on possible imaging applications by reporting preliminary imaging experiments and by investigating possible solutions to improve the output power.

References

\[2\] S. Blin et al., *Journal of Selected Topics in Quantum Electronics*, to be published (2017)
Optical monitoring of OH radical using advanced Faraday rotation detection approach

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The hydroxyl radical (OH) is one of the dominant oxidising specie in the atmosphere. It is considered as a primary agent that is responsible to remove a majority of traces gas emitted into the atmosphere, including greenhouse gas (CH₄), volatile organic compounds (VOCs) and substances harmful to health (CO, SO₂) [1], [2]. It is also responsible to initiate the reactions leading to the formation of a wide range of secondary species such as ozone (O₃) and secondary organic aerosols (SOAs) [3]. Reliable and real-time assessment of the OH radicals concentration change and related chemical process in the atmosphere is therefore a key factor to exactly determinate the oxidation capacity of the atmosphere. Because of its very high reactivity, very short lifetime (≤ 1 s) associated with very low atmospheric concentration (~ 10⁶ OH radicals/cm³), the development of novel instrument allowing accurate, interference-free and ultra-high sensitivity in-situ direct measurement of absolute OH concentration presents a great challenge for atmospheric science and climate change research.

We report in this paper our recent development of an interband cascade laser (ICL) spectrometer operating at 2.8 µm for OH radical measurement using Faraday rotation spectroscopy (FRS) [4]. FRS can be considered as a sensitive, selective and background-free detection method for paramagnetic molecules and radicals such as O₂, NO, NO₂, OH [5]–[7]. This is mainly due to its insensitivity to non-paramagnetic molecules present in the atmosphere such as H₂O or CO₂. The first prototype instrument, using only an optical absorption path-length L~25 cm, allowed us to achieve a 1σ (SNR=1) detection limit of 8.2×10⁸ OH radicals/cm³ [8], [9]. As the Faraday effect on the rotation of the probing light polarization is proportional to the sample absorption path length, implementation of a long absorption path length could allow us to lower the detection limit of the instrument. FRS coupled to a multipass cell with an effective optical absorption path-length of ~1200 cm is under investigation.

References
Ge-rich graded-index Si$_{1-x}$Ge$_x$ integrated optical interconnects: Towards a nonlinear platform for MID-IR integrated photonics

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Mid-IR systems are recently gaining attention due to the foreseen outstanding functionality of a large pool of devices upon integration in an efficient, compact and cost-effective platform [1]. Such new approach is expected to provide solutions in many fields including sensing, imaging, healthcare or secure communication networks, among others [2]. In that framework, the use of Si-based platforms has been proposed due to the good prospects envisaged to develop mid-IR photonic integrated circuits with multidisciplinary functionalities. A particularly interesting approach is the one that combines Si and Ge as raw materials as it allows to access to the mainstream CMOS technology [3-5]. Furthermore, the large transparency window of both materials ($\lambda = 8 \mu m$ for Si and $\lambda = 14 \mu m$ for Ge) provides a good scenario to develop label-free ultra-sensitive sensors by means of absorption spectroscopy. Moreover, the lack of Two-Photon Absorption (TPA) at this range of wavelengths may be leveraged to design efficient active devices using the Si and Ge third-order optical susceptibility. Thus, interesting phenomena such as four-wave mixing or supercontinuum generation may be addressed to develop wideband light sources in the mid-IR.

In this work, we present our recent work towards the development of functional mid-IR integrated photonic devices using the SiGe platform. For that, graded-index Si$_{1-x}$Ge$_x$ layer stacks with increasing Ge concentration were fabricated to provide gradual accommodation of the lattice mismatch from the Si substrate up to Ge, hence obtaining a Si$_{1-x}$Ge$_x$ buffer layer with a low density of threading dislocations. Low-loss Ge-rich waveguides with losses $< 2$ dB/cm in both polarisations have been demonstrated using this approach [6]. Additionally, the graded-index composition has been leveraged to design mid-IR waveguides with flat anomalous dispersion and an optimum gamma parameter over a broadband wavelength range, showing its potential to develop wideband monolithic mid-IR light sources [7]. Finally, the route map to develop mid-IR ring resonators based on such Ge-rich graded-index Si$_{1-x}$Ge$_x$ platform will be discussed by providing the main design rules and preliminary characterization results.

**Fig. 1.** (Left) SEM image of a fabricated Ge-rich Si$_{1-x}$Ge$_x$ waveguide, showing a smooth waveguide facet. (Right) Corresponding FDM simulation of the propagating quasi-TE optical mode in the waveguide at $\lambda = 4.6 \mu m$. 
Laboratory spectroscopy, especially at THz and mm-wave ranges require the advances in instrumentation techniques to provide high resolution of the recorded spectra with precise frequency measurement that facilitates the mathematical treatment.

We report the first implementation of a Schottky heterodyne receiver, operating at room temperature and covering the range between 530 and 590 GHz, for molecular laboratory spectroscopy. A 530-590 GHz non-cryogenic Schottky solid-state receiver [1] was designed at LERMA, Observatoire de Paris and fabricated in partnership with LPN-CNRS (Laboratoire de Photonique et de Nanostructures), and was initially developed for ESA Jupiter Icy Moons Explorer (JUICE), intended to observe Jupiter and its icy moon atmospheres. It is based on a sub-harmonic Schottky diode mixer, designed and fabricated at LERMA-LPN, pumped by a Local Oscillator (LO), consisting of a frequency Amplifier/Multiplier chain (AMC) from RPG (Radiometer Physics GmBh). The performance of the receiver was demonstrated by absorption spectroscopy of CH₃CH₂CN with Lille’s fast-scan DDS spectrometer. A series of test measurements showed the receiver’s good sensitivity, stability and frequency accuracy comparable to those of 4K QMC bolometers, thus making room-temperature Schottky receiver a competitive alternative to 4K QMC bolometers to laboratory spectroscopy applications. We will present the first results with such a combination of a compact room temperature Schottky heterodyne receiver and a fast-scan DDS spectrometer.

This work was funded by the French ANR under the Contract No. ANR-13-BS05-0008-02 IMOLABS.

Recent detection of methyl isocyanate (CH$_3$NCO) in the Orion [1], towards Sgr B2(N) [2] and on the surface of the comet 67P/Churyumov-Gerasimenko [3] motivated us to study another isocyanate, methoxy isocyanate (CH$_3$ONCO) as a possible candidate molecule for searches in the interstellar clouds. Neither identification or laboratory rotational spectra of CH$_3$ONCO has been reported up to now. Methoxy isocyanate was synthesized by the flash vacuum pyrolysis of N-Methoxycarbonyl-O-methyl-hydroxylamine (MeOC(O)NHOMe) at a temperature of 800 K. Experimental spectrum of CH$_3$ONCO was recorded in situ in the millimeter-wave range (75-105 GHz and 150-330 GHz) using Lille’s fast-scan fully solid-state DDS spectrometer. The recorded spectrum is strongly perturbed due to the interaction between the overall rotation and the skeletal torsion. Perturbations affect even rotational transitions with low Ka levels of the ground vibrational state, appearing in shifting frequency predictions and intensities distortions of the lines. The interactions are significant due to the relatively small vibrational energy difference (50 cm$^{-1}$) between the states and different representations of the Cs symmetry point group for the ground (A$'$), $v_{18} = 1$ (A$''$) and $v_{18} = 2$ (A$'$) vibrational states, thus leading to a “ladder” of multiple resonances by means of $\alpha$-, and $b$-type Coriolis coupling. The global fit analysis of the rotational spectrum of methoxy isocyanate using Coriolis coupling terms in the ground and two lowest vibrational states ($v_{18} = 1$ and $v_{18} = 2$) will be presented.

This work was funded by the French ANR under the Contract No. ANR-13-BS05-0008-02 IMOLABS.

8H30 : Welcome

9H00 : Session 3 - Molecular Spectroscopy

Chairman : M. Bernier

9H00 : T1 - D. Romanini
«High precision absorption spectroscopy in the optical domain using high finesse cavities»

9H30 : T2 - W. Chen
«Applications of spectroscopic techniques to trace gas sensing»

9H45 : T3 - M. Vieille Grosjean
«THz de-excitation of Rydberg atoms»

10H00 : T4 - B. Lavorel
«Free induction decay and field-free orientation of molecules induced by single-cycle THz pulses»

10H15 : T5 - A. Cuisset
«THz rotational spectroscopy of weakly polar CH$_3$D and non-polar CH$_4$ molecules using a widely tunable photomixing synthesizer based on a frequency comb»

10H30 : T6 - A. Roucou
«Internal rotation potential and pure rotational spectroscopy of 3-nitrotoluene»

10H45 : *** Coffee break ***
High precision absorption spectroscopy in the optical domain using high finesse cavities

Spectroscopie d’absorption haute sensibilité à l’aide d’un résonateur optique

D. Romanini

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En spectroscopie d’absorption le chemin optique détermine la sensibilité des mesures. L’utilisation d’un système optique multi-passage est une solution évidente dont on connait plusieurs implémentations. Moins triviale est l’utilisation d’un résonateur ou cavité optique. Dans sa réalisation la plus simple, deux miroirs sont alignés sur l’axe optique et la lumière transmise par le miroir d’entrée reste piégée entre eux, avec une petite fraction qui est retransmise par le miroir de sortie à chaque aller-retour. Cela demande que la fréquence optique satisfasse une condition de résonance. Lorsque on utilise des miroirs de très haute réflectivité le chemin effectif de la lumière dans la cavité devient très grande et largement supérieure de celui qu’on peut atteindre dans un système multipassage, en gardant un volume d’échantillon réduit. Cependant les résonances de la cavité deviennent très étroites et obligent l’utilisation d’une source de lumière laser, avec un spectre d’émission étroit, plutôt qu’une source de faible cohérence telle une lampe ou une LED. D’autre part on gagne ainsi en résolution spectrale non seulement par l’utilisation d’un laser mais aussi par l’exploitation des résonances de la cavité.

Comment mettre à profit le grand chemin d’absorption que la lumière doit parcourir dans la cavité avant de pouvoir s’en échapper ? Une méthode consiste à interrompre l’injection de la cavité pour générer une décroissance exponentielle de la lumière transmise, dite signal de ring-down (d’où « cavity ring-down spectroscopy »). La constante de temps exponentielle diminue sensiblement quand l’absorption intra-cavité augmente. Une autre méthode est de mesurer simplement l’intensité transmise à la résonance, ce qui va sous le nom de « cavity-enhanced absorption spectroscopy ». Conceptuellement plus simple, cette méthode délivre des bons résultats si combinée avec un asservissement fréquentiel du laser sur les résonances de la cavité (donc finalement elle est plus compliquée). Dans l’exposé je vais passer en revue les quelques variantes les plus utilisées de ces deux méthodes de spectroscopie d’absorption de haute sensibilité, ainsi que leurs avantages et inconvénients.
Applications of spectroscopic techniques to trace gas sensing

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In this talk, we will overview our recent progress in the developments of laser-based instruments dedicated to spectroscopic monitoring of key molecular trace gases of environmental interest. The newly developed photonic instruments will be presented which are based on modern infrared laser sources (external-cavity quantum cascade laser, distributed feedback quantum cascade laser and interband cascade laser) coupled to high-sensitivity spectroscopic measurement techniques (such as multipass absorption spectroscopy [1], quartz-enhanced photoacoustic spectroscopy [2], Faraday rotation spectroscopy [3] as well as laser heterodyne radiometry).

Typical applications in intensive field campaigns, in smog chamber and in laboratory investigation will be illustrated and discussed.

References


THz de-excitation of Rydberg atoms

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Many experiments at CERN like AEGIS aim to study antimatter behavior under gravity. For this purpose antihydrogen atoms are produced in a cryogenic cavity in Rydberg states. They have then to reach the ground state to have a lifetime long enough to measure gravity effects. The main problem of such experiment is that the spontaneous decay toward the ground state is too slow. We propose an experiment to study the possibility to achieve these transitions faster, using THz radiation [1][2]. For this purpose a sufficiently broad and continuous THz source shall be used in order to contain all the frequencies needed to stimulate the different transitions. The challenge we have to overcome is to drive the THz light into the vacuum chamber.

References
We investigate experimentally and theoretically the interaction between single-cycle terahertz (THz) pulses and molecules of different symmetry. The terahertz pulses are generated by focusing two-color femtosecond laser pulses in air and show a temporal shape close to a single-cycle pulse. We present two applications of the experimental apparatus. First, field-free orientation of the symmetric-top molecule CH$_3$I is observed by focusing the THz pulses in a short gas cell and measuring the free induction decay (FID) with the electro-optical detection (EOD) technique. The degree of orientation is deduced from numerical simulations [1]. Secondly, we measured the FID of the asymmetric-top molecule H$_2$O in atmospheric air with both EOD and terahertz field-induced second harmonic generation (TFISH) techniques [2]. Experimental results and simulated signals are compared directly in the time domain for short and long propagation length, leading to a good agreement between them in both cases (see Fig.1). Finally, we discuss the advantages/disadvantages of the two experimental techniques.

References
THz rotational spectroscopy of weakly polar CH₃D and non-polar CH₄ molecules using a widely tunable photomixing synthesizer based on a frequency comb

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The Terahertz (THz) group of the Laboratory of Physical Chemistry of the Atmosphere has developed a THz synthesizer exploiting a photomixing source widely tunable between 0.3 and 3.3 THz with a frequency metrology precise to the ten kHz through the locking of optical laser sources on an ultra-stable frequency comb. The performances of this unique instrument contribute to improve and complete international databases such as HITRAN or JPL by means of rotational spectroscopy studies (positions and line profiles) on stable and unstable species that play a key role in Earth or planetary atmospheres.

Recently, the sensitivity thresholds have been overcome through measurements on deuteromethane CH₃D, a primary target for measurements of the origin of atmospheric gases and methane CH₄, one of the most abundant gases in planetary atmospheres. Direct THz absorption measurements between 1 and 2.5 THz have been performed with an optical path of 20 m allowing line positions and line profiles studies of rotational transitions with intensities lower than 10⁻²⁵ cm⁻¹/(molecules.cm⁻²). In the case of CH₃D, the line positions of K multiplets with 6 < J < 10 have been measured for the first time with relative uncertainties better than 10⁻⁷ allowing to improve the accuracy of ground state molecular parameters and consequently, the prediction of pure rotational frequency and intensity transitions in the THz domain. In addition, a first determination of self-broadening coefficient from pure rotational transitions of CH₃D have been performed with measurements in a small pressure range from 1 to 4 mbar. Finally, we demonstrated the capability of the THz synthesizer to measure THz pure rotational transitions of non-polar CH₄ molecules where a very weak transition dipole moment is induced by centrifugal distortion effects. Our new measurements in the 2.5 THz region were compared with the distortion dipole rotational spectrum of CH₄ measured by Boudon et al. using synchrotron based FT-Far-IR spectroscopy. With a resolution of the order of tens of kHz, we improved by at least 2 orders of magnitude the accuracy of measured line frequencies providing a better agreement with simulations based on the tensorial formalism developed in the Dijon group for spherical-top molecules.

References
Internal rotation potential and pure rotational spectroscopy of 3-nitrotoluene

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Nitrotoluene compounds are semi-volatile organic molecules of environmental and military interest. They are widely used in dyestuff, pesticides, rubber and pharmaceutical manufacturing [1]. Persistent in natural conditions, they are difficult to oxidize due to the strong electron-withdrawing effect of the nitro group [2]. Moreover, they are derivative products and taggants of the very well-known explosive TNT.

In a previous study, gas phase Far-IR vibrational cross-sections have been measured using FT-FarIR spectroscopy based on the AILES beamline of the SOLEIL synchrotron facility [3]. Even at the maximum resolution of the interferometer, it was not possible to resolve rotationally the Far-IR spectra at room temperature. In this study, we present the first high resolution analysis of 3-nitrotoluene (3-NT).

Pure rotational measurements were performed in jet-cooled conditions and at room temperature using the Fourier Transform MicroWave (FTMW) spectrometer [4] located at the PhLAM (2-20 GHz range) and the submm/THz frequency multiplication chain [5] located at the LPCA (70-220 GHz range), respectively.

The FTMW data have been analysed using the BELGI-Cs program [6] taking into account both the internal rotation motion and the hyperfine structure of 3-NT. The FTMW measurements allowed a first determination of the rotational constants, of the quartic centrifugal distortion constants, of the hyperfine structure constants due to the nuclear quadrupole coupling of nitrogen and of the internal rotation parameters characterized by a very low barrier height (calculated at about 6 cm⁻¹).

In the submillimeter domain, a weak and very congested spectrum with many blended lines was observed because of the high number of low-frequency vibrational and torsional excited states. The analysis has been achieved by combining Kisiel’s (ASCP and SVIEW) and Pickett’s (SPFIT SPCAT) programs in support to the use of the BELGI-Cs program. The analysis permitted a determination of high order internal rotation parameters, and therefore a determination of the internal rotation potential.

References
11H00 : Session 4 - SATT Session

Chairman : F. SIMOENS

Special session managed by the French agency for acceleration the transformation of French research into innovations

11H00 : T7 - F. Friederich
«Terahertz Imaging in Industry»

11H15 : T8 - C. Poulin
«Study of materials, devices and systems in terahertz domain by analogy with optical methods»
Within the recent decade many different active terahertz imaging systems have been developed, as exemplary given in [1]. Potential suitable concepts for industrial applications range from fast quasi-optical single- or few-pixel scanning approaches [2] over integrated multi-pixel camera solutions [3] to mono- or multi-static synthetic imaging setups [4]. While nowadays especially commercialized integrated terahertz cameras receive a great interest, many industrial application scenarios require individually designed terahertz imaging solutions, which profit from the wide variety of previously developed terahertz imaging concepts. Within this contribution, our recent industrial projects, which concern the realization of customized imaging systems, will be addressed. Furthermore, our latest developments of a sparse multi-static imaging concept for future industrial 3D terahertz inline-inspection will be discussed.

References
Study of materials, devices and systems in terahertz domain by analogy with optical methods

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‘Terahertz Waves Technologies’ company provides 2D and 3D contactless and nondestructive control imaging systems to analyse the inner and outer structure of materials for the scientific and industrial sectors [1]. Depending on sample shape, size and customer’s problematics, we try to find the optimal optical configurations in transmission and/or reflection modes. Today, we need to improve our understanding of the THz images. A way to accomplish it consists on increasing our knowledge of the physical phenomena involved.

In this context, we develop electromagnetic models [2, 3, 4] to describe interactions between THz waves and matter. As a first step, we simulate the optical response of homogeneous and planar polymers samples. Recently, we obtained a good agreement with experimental results. Therefore, we are encouraged to enlarged our study to heterogeneous samples which represent currently industrial samples. Furthermore, we will consider more complex phenomena in our models like the roughness and the diffusion. In the future, we wish to use these developed models as a predictive tool. This means that we hope to simulate optical response of a sample without imaging it.

References
14H00 : Demonstration of THz Telecom Transmission

G. Ducournau

14H40 : *** Coffee break ***

15H00 : Session 5 : Imaging and Application (1)

Chairman : V. Vaks

15H00 : T9 - L. Chusseau
«mm-waves near-field measurements»

15H30 : T10 - C. Prophete
«Quantitative Analysis of THz Imaging Systems In Brownout Conditions»

15H45 : T11 - J.P. Guillet
«Frequency modulated continuous wave imaging for art painting defect analysis»

16H00 : T12 - F. Bonnefoy
«Authentication in the THz domain: a new tool to fight counterfeiting»

16H15 : T13 - M. Sypek
«Diffractive structures for broadband THz range beam shaping»

16H30 : *** Coffee break ***
High efficiency UTC Photodiode for High Spectral Efficiency THz links

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Due to an increasing demand of data transmissions capability, the THz band, precisely beyond 200 GHz, has been shown to be very interesting to pave the way for next generation wireless communications [1]. While potential standard currently investigated is the 100 Gbit/s data rate [2], proof of concept using photonics-based THz emitters (photomixers) and broadband receivers already lead to early advanced demonstrators [3]. In this work, a high-efficiency/high power photomixer based on unitravelling carrier (UTC) photodiode is presented, and a first THz link using this device. In the proposed device, a semi-transparent top contact based on sub-wavelength apertures covering a large fraction of the UTC-PD surface with metal is used, resulting in a small contact resistance and high transmittance at 1.55 µm. The contact consists of parallel metallic strips of width w, aperture a, and metallization height h. Fig. 1 shows the topology of the device, as well as parameter set used for top-contact. A resonant cavity with metallic mirror under photodiode was used in these devices in order to increase the responsivity. For example, Fig. 2 shows that the measured RF power for a 3*3 µm² device was > 600 µW at 300 GHz, for a 8.5 mA current and -1 V bias. The fabricated UTC-PDs were used for wireless communications at 300 GHz. For a link of about 1.5 meter, a 4*4 µm² UTC-PD, QAM-16 constellation was successfully recovered at 32 Gbit/s using a limited optical power around 20 mW.

![Fig. 1. Output power of the UTC-PD device and QAM-16/eye-diagram after 1.5 m propagation distance.](image)

This work is supported by the ANR under COM’TONIQ ANR-13-INFR-0011-01 program, the DGA, RENATECH Network and Lille 1 university. This work was also supported in part by the equipex FLUX and ExCelsior projects and the Nord-Pas de Calais Regional council, and the FEDER through the CPER Photonics for Society. Some of the work was also supported by an IEMN-Lille University-Tektronix academic-industrial partnership on THz communications.

References


http://www.ieee802.org/15/pub/index_TG3d.html

Since years, we have developed many near-field experiments using CW millimetre wave sources in the 60–100 GHz band with aim of a high-resolution imagery [1,2,4], a material characterization [3,5], or the evaluation of electronic circuit immunity [6]. Image formation and resolution intimately depends on the probe to sample interaction, which is dictated by the probe type via its predominant electric field component, and also on the signal acquisition technique, which separate near-field and far-field contributions. As such VNA are hugely affected by far-field components that are only removed using a vibrating probe and a lock-in detection, thus requiring home-made mm-wave systems. Nevertheless, measurement results still mix either topological, material dependent and polarization effects that must be elucidated for correct interpretation and optimization. A record resolution of 2 \( \mu \)m @60 GHz was thus obtained with pyramidal antennas (Fig. 1 left) [4]. Work in progress is currently to integrate these performances with a vector detection for more accurate material discrimination.

When high spatial resolution is not needed, very simple microwave systems with open waveguides are very efficient and low cost. We built such systems for material characterization with chirped sources [5] to characterize material dispersion, and for a totally different purpose of direct IC perturbation via electromagnetic injection (Fig. 1 right) [6]. This last experiment is novel and reveals possible new threats toward security and cryptography of numeric ICs.

References
Quantitative Analysis of THz Imaging Systems In Brownout Conditions

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Brownout refers to dust cloud created by the rotor downwash of a helicopter. When it occurs, the visibility becomes limited, or even null. The pilot can be disorientated and accident may happen. No existing imaging systems can see through dust clouds, in real-time and with sufficient resolution. Using waves between 100 GHz and 1 THz seems to be a good solution to make a compact and suitable imaging system.

First, we define a brownout model based on spherical particles with refractive index of silica with radius following the Marshall-Palmer distribution [1, 2]. The atmosphere attenuation is taken into account. We then establish theoretically the power balance of the involved sources of signal (ballistic signal from the source) and noise (backscattered source power, thermal radiations of ground and sky). This analysis is made for a photometric detection system and with one compounded of antennas.

The backscattered power noise is evaluated with a Monte Carlo simulation, combined with Mie theory, to solve the Radiative Transfer Equation [3]. Thermal radiations are estimated from the Planck function [3]. One result of the simulation is shown in figure 1.

Fig.1. Comparison of signal and noise powers detected by one photometric or one antenna-based pixel at the central frequencies of the atmosphere transmission windows (frequencies and matching wavelengths written in the figure)

Finally, this work indicates that the thermal radiations is negligible compared to signal and backscattered noise. The best configuration is a bistatic imaging system. Hence, a compact THz imaging system seems very promising to image over tens of meters. The challenge remains in the development of appropriate technology (powerful THz source, small and sensitive detectors...). This system can play an important role as for military or civilian missions in desertic areas.

References

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Frequency modulated continuous wave imaging for art painting defect analysis

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Terahertz non-destructive testing is a well-known technique for analysis of art painting. Several works have shown detection of hidden layers and defects with terahertz pulses [1,2]. In a previous work, we have shown that terahertz radiation can detect defects in the context of a restoration of a painting [4,5] with a speed increase compared to time domain imaging, which implies the ability to scan an entire painting. Our system, working in transmission and reflection imaging at 100 GHz and 300 GHz was able to detect voids between painting and canvas and underlining glue discontinuities. Then, the painting was restored (cleaning and removing vanish first) and we add a fixative layer and a gluing of the pictorial layer on the canvas using historical methods and process. For this, we made an injection of rabbit skin glue inside the zones of air bubbles to join the both canvas together. This technique of restoration allows to repair locally the painting avoiding a total relining. We will demonstrate (on Fig 1) that voids have been filled and no longer appears on the image made after restoration and that millimeter wave imaging is an efficient tool for art science and restoration.

Fig.1. Left : Photography of painting. Center: 300GHz reflection image of the painting before restoration. The red surrounded areas are air voids between the pictorial layer and the canvas. Right: 300GHz reflection image of the painting after first step of restoration. The yellow surrounded areas have been restored

References
Authentication in the THz domain: a new tool to fight counterfeiting

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Introduction: In the present work, we propose a new approach based on the use of the spectral signature of diffraction gratings engraved on one side of smart cards to be authenticated. The etched substrate acts as a dielectric waveguide associated to a 1D diffraction grating [1]. When the coupling conditions are verified, the reflected and transmitted THz spectra exhibit extinction lines (m-lines) that can be used as a broadband and rich spectral signature. For a given incident angle, the number of m-lines, their frequency positions and depth depend on the geometrical dimensions of the structure [2]. Hence, a unique etching scheme leads to a unique spectral signature. We first focused on simulations and experimental validation of the proposed authentication method that we would present to the 9th THz days.

Structure and principle: The structure presented in Fig. 1.a is constituted in a 1D rectangular diffraction grating engraved on a smart card using a LPKF Protomat C60 machine. The optical parameters of the cards are: thickness $e_{\text{card}} = 760 \pm 10 \, \mu\text{m}$, absorption $\alpha \sim 20 \, \text{cm}^{-1}$ and refractive index $n \sim 1.72$ @ 1 THz. The transmission and reflection of whole structure is simulated using a homemade software based on the differential method [3]. The structure considered as the reference one has grating period $\Gamma = 800 \, \mu\text{m}$, grooves depth $p = 200 \, \mu\text{m}$, and has been characterized under incident angle $\theta = 10^\circ$. These values have been chosen to obtain a sufficient number of m-lines in the THz signature from 200 GHz to 800 GHz.

Results: Authentication process is based on the possibility to discriminate two slightly different THz signatures: 1) the reference structure described above and 2) a structure whose parameters have been slightly modified. For that purpose, we calculate correlation coefficient (CC) of both signatures. The results of the authentication process are presented in Fig. 1.b. To enlighten the sensitivity of the THz signature relatively to the variation of the grating depth, we calculate the CC on the transmission (green line and dots) and on the second derivative (blue line and dots) of structures whose grating depth differs from the reference one over a range of 100 $\mu$m. According to Fig. 1.b, CCs calculated from 2nd derivatives of the spectral signatures is dedicated to authentication purpose since it drops steeply to 0 with depth variation of grooves of only tens of $\mu$m.

Conclusion: In this study, we showed the possibility to authenticate smart cards in the THz domain using a diffractive grating structure directly engraved on the devices. To authenticate such structures, we used the correlation coefficient as a very sensitive authenticator when calculated on the 2nd derivatives of the THz signature. We also show that a change of the geometrical size of the grating as small of several $\mu$m lead to a significant and sufficient modification of the THz signature to be used in authentication process with the objective to oppose counterfeiting.

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References
Diffractive structures for broadband THz range beam shaping

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To fully exploit the potential of the sub-THz and THz range of the e-m radiation it is necessary to provide effective both sources and detectors. Also a high performance THz optics systems seems to be necessary to design and manufacture useful devices. Different solutions in the case of the optical path in such devices can be applied. Typically refractive and reflective optics is considered. It is worth to notice that a technological breakthrough in the field of the flat optics systems manufactured by 3D print technology was achieved during last years (sub-wave optics, diffractive optics, metamaterials).

Significant results in the field of THz beam shaping were obtained by the use of the diffractive optics. The diffractive structures have many advantages such as light weight, small thickness (therefore lower absorption) and compactness. In addition, in the case of applying them for THz radiation range, they are relatively cheap to produce by mechanical milling or 3D printing. The main disadvantage of the diffractive structures is their huge chromatic aberration.

Diffractive optics is very efficient in the case of the narrowband (quasi-monochromatic) illumination. Designing of the broadband diffractive optical systems could significantly increase range of application for existing THz and sub-THz devices. In this paper we evaluate the chromatic properties of selected diffractive elements useful in THz and sub-THz range.

References
17H00 :  **Session 6 : Imaging and Application (2)**

*Chairman : S. Houver*

17H00 :  T14 - V. Vaks  
«Terahertz and multichannel spectroscopy for breath research»

17H30 :  T15 - F. Bondu  
«Submillimetre spectroscopy of the volatile metabolome»

17H45 :  T16 - J.-L. Coutaz  
«Determination of water vapour concentration in atmosphere with a drone mounted frequency domain THz spectrometer»

18H00 :  T17 - A. Al-Ibadi  
«THz Spectroscopy and Imaging for Breast Cancer Detection in the 300-500 GHz range»
Terahertz and multichannel spectroscopy for breath research

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At present the development of analytical spectroscopy with high performance, sensitivity and spectral resolution for exhaled breath research is of great importance. Two-channel high resolution THz spectroscopy and high resolution subTHz-THz-IR spectroscopy are presented. Development of a multi-channel gas analyzer increases the number of gases that can be identified and the reliability of the detection by confirming the signature in subTHz, THz and MIR ranges. The testing measurements have testified this new direction of analytical spectroscopy to open widespread trends of its using for various problems of medicine and biology. First of all, there are laboratory investigations of the processes in exhaled breath and studying of their dynamics. Besides, the methods presented can be applied for detecting intermediate and short time living products of chemical and biological reactions in exhaled breath. The gas analyzers have been employed for investigations of acetone, methanol and ethanol in the breath samples of healthy volunteers and diabetes patients. The results have demonstrated an increased concentration of acetone in breath of diabetes patients. The dynamic of changing the acetone concentration before and after taking the medicines is discovered. The potential markers of pre-cancer states and oncological diseases of gastrointestinal tract organs have been detected. The changes in the NO concentration in exhaled breath of cancer patients during radiotherapy as well as increase of the NH₃ concentration at gastrointestinal diseases have been revealed. The preliminary investigations of biomarkers in subTHz, THz and MIR ranges have demonstrated the advantages of the multi-channel high resolution spectroscopy for noninvasive medical diagnostics.
Submillimetre spectroscopy of the volatile metabolome

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Gaseous ensembles of molecules, called the volatilome, are fingerprints [1]–[3] of the metabolism of living organisms, including bacteria and archeobacteria. The submillimetre spectroscopy of these mixtures [4] could provide an interesting analysis alternative to gas chromatography coupled to mass spectroscopy (GC-MS) as there would be less effects (heating, ionization) damaging the integrity of large molecules. The characterization of ensembles would then in medical situations [5], [6] discriminate pathological situations or possibly identify bacteria resistant to antibiotics, and in food industry [7], [8] survey fermentation processes. The realization of an instrument meets several challenges. (a) The optical generation of submillimetre waves promises to attain a large frequency span, thus a large molecule span: we will present results towards such a compact and tuneable source. (b) The detection system should present a large signal to noise ratio, in order to detect molecules at trace levels. (c) The sampling system should take care that a large fraction of volatile biological molecules are actually liquid at ambient temperature and pressure.

References

Determination of water vapour concentration in atmosphere with a drone mounted frequency domain THz spectrometer

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THz spectroscopy is a useful tool for gas analysis because very specific rovibrational transitions for a large variety of molecules occur in this frequency domain. Under the right conditions, these transitions may be used to measure the presence and concentration of different molecules in a gas sample, like volatile organic molecules [1] that cannot be detected or monitored in other spectral domains. Moreover, absorption lines are less broadened by Doppler effect and thus THz spectral selectivity is better than in VIS or IR. Finally, THz spectroscopy is less sensitive to fog, smoke or dust in the atmosphere. While a significant effort has been made to prove the ability of a laboratory based frequency domain THz spectroscopy to quantify different gases [2], very little has been done in the field regarding atmosphere because of the lack of portable THz spectrometer. Here, we report on the first in-situ study of water vapour concentration in atmosphere using a CW THz spectrometer attached to a drone (Fig. 1). The drone is a DJI-S1000 Octocopter, which has a maximum lift-off weight of 11 kg (6 kg allowance) and a flight time of 15 minutes. The THz spectrometer was a PB7220 system from Bakman Technologies, specially adapted in size and weight to be carried by the drone. The spectrometer is based on photomixing in photo-conducting antennas and homodyne detection [3]. A test flight was performed at Paramount Ranch Park in Agoura Hills, CA, with reported humidity levels in the 75 to 85% range [4]. The absorption coefficient of air was measured 10-m above ground. Fig. 2 shows the recorded absorption spectrum, together with absorption spectra calculated with the model by Slocum et al. [9], for 2 different humidity percentages (50 and 90%). By fitting the experimental data with the model at 1185 GHz (at this frequency, data are not perturbed by the spectral resolution and are largely over noise), we found that the humidity of the tested atmosphere is 81% (± 15%).

Fig. 1. The modified PB7220-2000-T airborne spectrometer attached to the drone.

Fig. 1. Recorded and calculated absorption spectra of air.

References
THz Spectroscopy and Imaging for Breast Cancer Detection in the 300-500 GHz range

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Spectro-terahertz (THz) imaging is a burgeoning field since the high sensitivity of submillimeter waves to tissue water concentration has been brought to light (Woodward et al., 2002). In addition, it has been demonstrated previously, the significant water concentration difference between normal and abnormal tissues (Ross and Gordon 1982). Hence, we draw-up the report on our technological progresses led with both Transmission and Reflection mode to discriminate breast malignant tissues from healthy ones. In this work, we focus on the optical properties of different freshly excised human tissues on a single point measurement that are extracted through a dedicated home-made algorithm, following fan et al, 2016 procedure. We can access to a dielectric property map of the biological sample (Fig. 1). It may provide, from the knowledge of this optical property picture, precious information to diagnose and to identify the cancerous regions during the analysis. Then, we propose a rigorous procedure to ensure the repeatability and the accuracy of our techniques. Next, we will show some images obtained in this frequency range (Fig. 2 H. Balacey et al 2016). This crucial step will provide access to both chemical and physical interactions between THz radiations and human biospecimens for each sample preparation step and prepare interpretation of near field analysis at 550 GHz chosen frequency for its contrast perspectives of tissues (J. Grzyb et al 2017).

Fig 1: THz properties for water and breast tissue. Refractive index and absorption coefficient of bad and normal tissue in the THz range

Fig 2: a) visible image of fresh breast tissue. THz images of raw data-reflection for fresh tissue as: frequency domain image at 0.3, 0.4, & 0.5 THz respectively

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References


8H30 : Welcome

9H00 : Session 7 - Sources (THz and MIR)

Chairman : D. Romanini

9H00 : W1 - T. Yasui
«Gapless dual THz comb spectroscopy»

9H30 : W2 - J.-F. Lampin
«A continuous wave terahertz molecular laser pumped by a quantum cascade laser»

9H45 : W3 - Y. Cordier
«Wide bandgap semiconductors for IR and THz: GaN vs ZnO»

10H00 : W4 - R. Teissier
«Growth and fabrication of THz quantum cascade lasers»

10H15 : W5 - Z. Loghmari
«Continuous wave operation of InAs-based quantum cascade lasers above 20 μm»

10H30 : *** Coffee break ***
Gapless dual THz comb spectroscopy

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Terahertz (THz) frequency comb is a powerful tool for broadband high-precision THz spectroscopy because a series of comb modes can serve as frequency markers that are traceable to a frequency standard. However, a mode distribution that is too discrete limits the spectral sampling interval to the mode frequency spacing even though individual mode linewidth is sufficiently narrow. In this paper, using a combination of a spectral interleaving and dual-comb spectroscopy in THz region, we achieved a spectral sampling interval equal to the mode linewidth rather than the mode spacing.
A continuous wave terahertz molecular laser pumped by a quantum cascade laser

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We demonstrate a new approach to realize a continuous wave (CW) THz laser source that can be used as a local oscillator. It is based on a molecular gas optically pumped by a mid-infrared beam. Generally optically pumped terahertz lasers (OPTL) are pumped by CO₂ discharge lasers. They are bulky and have a low efficiency. Here we demonstrate for the first time the use of a solid-state mid-IR quantum cascade laser (QCL) as an OPTL pump laser [1]. The main advantage of the QCL is its continuous tunability compared to CW CO₂ lasers which are only tunable on discrete lines. It allows a larger degree of freedom in the choice of the molecule and in the transitions. Small molecules with large electric dipoles are good candidates to realize high efficiency and compact OPTL. Here, the active medium of the laser is made of low-pressure NH₃ gas enclosed in a cylindrical metallic waveguide closed by two flat mirrors (Fig. 1). The mid-infrared QCL work at room temperature and its beam is focused in the cylindrical cavity through an input coupler. It is tuned to a transition between a ground state level and a ν₂ = 1 excited state level of the NH₃ molecule. Population inversion is achieved between excited state levels. The molecules de-excite by stimulated emission on pure inversion “umbrella-mode” quantum transitions. These transitions are allowed by the tunnel effect and their frequencies are close to 1 THz [1,2]. We have already demonstrated a CW output power of 0.35 mW at 1073 GHz. More than ten other laser lines can be also obtained around 1 THz. The generated power is sufficient to pump HEB or Schottky diode mixers. We believe that this source can be used as a local oscillator for heterodyne receiver applications.

Fig. 1. Schematic of the THz NH₃ laser (inset: inversion process of NH₃).

References
Wide bandgap semiconductors for IR and THz: GaN vs ZnO

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ZnO and GaN are semiconductors with bandgap energies of ~3.4 eV. Their combination with ZnMgO and AlGaN alloys respectively offers the possibility to design multi-quantum well structures able to provide electron quantum confinement energies suitable for intersubband (ISB) transitions from the IR range to the THz range. If III-V semiconductors also present such properties with the demonstration of IR and THz quantum cascade detectors and lasers, the optical phonon energy is rather limited (36 meV for GaAs) and makes the use of cryogenic systems necessary. On the contrary, the large optical phonon energy of 72 meV for ZnO and 92 meV for GaN is a noticeable advantage to keep the inversion of population in a laser at temperatures superior to 300K. Another consequence is that compared to III-V’s the absorption Reststrahlen band is shifted to larger energies so that the entire 1-15 THz range is in principle accessible to ZnO and GaN.

Such an ideal picture is however spoiled by the lack of knowledge and technological maturity associated with these new material systems. To fill the gap, we work to the development of such multi-quantum well heterostructures within two projects named ZOTERAC [1] and OPTOTERAGAN [2]. A first objective is to grow high quality materials with non-polar crystal orientation in order to avoid the detrimental effect of internal electric field present at the different heterostructure interfaces and which severely complicates the design of the structures. If this can be achieved on ZnO thanks to the availability of high quality m-plane ZnO substrates, the quest for similar qualities on GaN is much more difficult and requested the fabrication of alternative semi-polar oriented GaN on patterned sapphire substrate to filter crystal defects like basal stacking faults [3]. Details on the grown ZnMgO/ZnO and AlGaN/GaN multi-quantum well heterostructures will be presented as well as the first results of absorption in the THz range.

References
Growth and fabrication of THz quantum cascade lasers

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A challenge for the emergence of many applications of Terahertz (THz) frequency radiation, such as imaging and chemical sensing, is to develop compact, low-cost, efficient THz sources. The development of the THz frequency quantum cascade laser (QCL) has provided a potential solid-state solution in that respect. Since their first demonstration in 2002, THz QCLs based on the GaAs materials system have become more mature compact sources of coherent radiation in the 1.2–5.4 THz band [1], with maximum operating temperatures of 200 K [2] and maximum peak pulsed output powers exceeding 1 W [3] being demonstrated.

The molecular beam epitaxy growth of THz QCL heterostructures is however still a complex and challenging task which is mastered only by a few research groups in the world. In this contribution, we report on the successful growth and fabrication of GaAs/AlGaAs THz QCLs emitting over a spectral range of 3.1–4.0 THz. Using a three-well resonant phonon active region design [4], devices based on both double metal (DM) waveguide and surface plasmon (SP) waveguide have been fabricated and studied. The lasers operate in pulsed mode up to a maximum temperature of 147 K (DM) and 118 K (SP), and with a peak output power collected from a single facet of 40 mW at 80 K for SP lasers (Fig. 1).

Fig. 1. Output characteristics of a DM QCL emitting at 3.2 THz (left), and a SP QCL emitting at 3.8 THz (right).

References
Continuous wave operation of InAs-based quantum cascade lasers above 20 µm

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The wavelength range between 20 and 60 µm is of great interest for many application such as spectroscopic sensing and astrophysics. Because of the difficulty of developing high-performances lasers sources at these wavelengths, this optical range is still underdeveloped. Indeed, in this region, absorptions by optical phonons of III- V semiconductors and free carriers are very strong. InAs/AlSb quantum cascade lasers (QCL) are promising for the development of far infrared lasers thanks to the small electron effective mass in InAs and to the resulting large inter-subband optical gain [1]. Recently we demonstrated QCLs made of InAs operating at a wavelength of 20 µm [2]. The low threshold current densities of 4.3kA/cm² in pulsed mode at room temperature that have been subsequently achieved confirmed the assets of the small effective mass in InAs.

Here, we report much lower threshold InAs/AlSb quantum cascade lasers emitting at 20.5 µm. The devices are based on an improved vertical design similar to those employed previously in [2], in which the doping level of the active core is considerably decreased. The lasers exhibit a threshold current density as low as 1.16kA/cm² in pulsed mode at room temperature and can operate in this regime up to 380K. The continuous wave regime of operation has been achieved in these devices at temperatures up to 180 K.

Fig.1. Electrical and optical output characteristics of InAs/AlSb QCL emitting above 20 µm in pulsed mode regime (left), and continuous wave regime (right). Insets show emission spectra in continuous wave regime.

References
11H00 : Session 8 - THz Optics and Waveguides Biophotonics

Chairman : L. Chusseau

11H00 : W6 - A. Shkurinov
«Introduction into nonlinear THz photonics: basis and their potential applications»

11H30 : W7 - G. Humbert
«Hollow-core terahertz waveguides based on photonic bandgap»

11H45 : W8 - O. Stepanenko
«THz Isolator Using Nonreciprocal Magnetoplasmonic InAs Mirror»

12H00 : W9 - M. Hamdi
«Enhanced Plant Water Status Measurement using THz Time-Domain Spectroscopy»

12H15 : W10 - G. Gallot
«Probing Living Cells by THz Attenuated Total Reflection. Application to Quantitative Permeabilization Measurement»

12H30 : W11 - J. Torres
«Out-of-equilibrium proteins dynamic probed by THz spectroscopy: towards Frohlich’s condensation»

13H00 : *** Lunch ***
Introduction into nonlinear THz photonics: basis and their potential applications

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The bright THz source is essential for exploring nonlinear THz field-matter interaction and spectroscopy. Recent advances in high peak-power pulsed THz sources with intensity greater than 1 MV/cm provided unique opportunities to study transient dynamics of non-perturbative states of matter and to investigate strong light-matter interactions. The records of pulsed THz field strength are in the range of 10 to 10 MV/cm from laser-induced gas plasma with two-color laser excitation in dry nitrogen, or up to about 80 MV/cm from organic crystals with the optical rectification. Extremely intense sub-cycle pulses pulse at THz/far-IR region will enable strong field-matter interaction and investigation of a wide range of scientific phenomena.

The present paper studies the generation mechanism of terahertz (THz) radiation from tightly focused femtosecond laser pulses in a gas medium. We measured the angular radiation pattern under different focusing conditions and observed that with the deepening of focus, the angular radiation pattern changes and optical-to-THz conversion efficiency increases. The analysis of the observed phenomena led to the assumption that the dipole radiation prevails in most cases despite the existing conception regarding the dominating role of the quadrupole mechanism of radiation. Based on these assumptions, the transient photocurrent theory of the phenomenon presented in this paper was developed by us and used for the numerical fit of the experimental data.

Conventional methods used to obtain the highly synchronized pulses necessary for the pump-probe measurements rely on an optical parametric oscillator (OPO) or optical parametric amplifier (OPA), which generates synchronized signal and idler pulses at different wavelengths. In the paper we will discuss the generation of two synchronized ultrafast radiations, THz and high harmonic radiation (XUV to soft X-ray), using an intense laser pulse in visible or near-infrared ranges with selected media such as gases and nano-structured metals. We studied THz and X-ray radiation from gas clusters while irradiating them with high-intensity femtosecond optical pulses. Clusters were produced by partial condensation of the pure Ar gas and the mixtures in the process of their expansion through a conical nozzle into evacuated chamber. Simultaneous measurements of THz and X-ray radiation properties were carried out with various durations and total energies of optical pulses, in single-color and two-color schemes of clusters jet irradiation. In the two-color scheme, optical pulse bears both the fundamental and second harmonics of Ti-Sapphire laser, we observed a significant increase of THz radiation field without any change of X-ray radiation properties. We observed a non-monotonic dependency of THz radiation power upon the pulse duration at given total energy of the optical pulse. To interpret this effect we developed a theoretical model of cluster ionization which self-consistently predicts level of ionization and electron temperature in the clusters.

These instruments, as synchronized THz, X-ray and XUV ultra-short pulses for jitter-free time-resolved pump/probe measurement, may be a unique platform for multi-dimensional ultrafast spectroscopy, nonlinear phenomena, and high-resolution (spatial and temporal) imaging. The tabletop nature of the instrument allows us to perform our research beyond previously limited national advanced light facilities.
Hollow-core terahertz waveguides based on photonic bandgap

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The development of waveguides is limited in the terahertz (THz) domain by the degradations of material properties. One way of beating this limit is by confining the electromagnetic field in an hollow-core waveguide with the help of a photonic band-gap (PBG) crystal that forbids field extension in the plane of the crystal.

The numerous studies on the PBG optical fibres with hollow or solid cores have led to remarkable demonstrations. The most important property of PBG guidance mechanism for the THz domain is the possibility to use materials that are too absorbent for wave guidance by total internal reflection mechanism. Stronger the PBG effect is, higher the confinement of light in the core is, yielding lower effect of material absorption on field attenuation.

Here, we exploit the properties of PBG optical fibres for developing THz waveguides that are composed of an hollow core surrounded by a 2D array of silica rods in air (Cf. Fig 1(a)). An appropriate diameter of silica rods leads to a transmission window around 0.55 THz with a reduction of the attenuation coefficient of the guided field by three orders of magnitude (from simulation) compared to the material absorption coefficient (Cf. Fig. 1(b)). As shown in Fig. 1(c), broader transmission windows is achieved by replacing rods with thin capillaries. Further theoretical and experimental studies on the influence of the shape and topology of the array of silica rods on the waveguide properties will be also presented.

Fig. 1. (a) Scheme of an hollow-core THz waveguide composed of an array of silica rods suspended in air. (b) Simulations of PBG properties and the attenuation coefficient of the core mode for different hollow-core diameters, and experimental demonstration of PBG guidance in hollow-core. (c) Simulations of PBG properties and experimental demonstration of transmission windows broadening by replacing rods by capillaries.
THz Isolator Using Nonreciprocal Magnetoplasmonic InAs Mirror

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Isolation is an important passive functionality in optics that helps to block any destabilizing feedback radiation. Creating an isolator demands breaking Lorentz reciprocity of Maxwell’s equations [1], which can be achieved using gyrotropic phenomena. As an example, Faraday rotation is the best known nonreciprocal (NR) magnetooptical (MO) effect commonly used for optical isolators. However, Faraday rotators at mid-IR and THz ranges have serious drawbacks, such as the need for a high applied magnetic field (~1 Tesla) necessary to achieve a reasonable polarization rotation, but more importantly high propagation losses, and bulky dimensions.

In the present work we demonstrate a NR magnetoplasmonic InAs mirror for THz and mid-IR isolation based on the transverse magneto-optical Kerr effect (TMOKE). This manifests itself as nonreciprocal reflection of p-polarized light from a transversally magnetized surface. By combining it with a surface plasmon resonance, TMOKE (which is commonly weak on a bare MO substrate) is greatly enhanced [2]. By using a reflective configuration for the nonreciprocal function, the problem with propagation losses through the gyrotropic material is avoided. The low effective mass of free carriers of a small gap semiconductor such InAs (m*=0.024m_e) allows both to realize a plasma frequency in the THz range and a cyclotron frequency (ω_c=eB/m*) in the same range with a reasonable value for the magnetic induction. By carefully designing 1D plasmonic gratings on the surface of the NR InAs mirror, TMOKE can be enhanced by 3 orders of magnitude. Chemically etched gratings have been fabricated in undoped InAs substrates (Fig.1a). Comsol calculations of the NR p-reflectivity on the obtained profiles predict isolation ratios close to 20 dB at room temperature and under an applied magnetic field of 1 Tesla (Fig.1b). Experimental reflectivity characterizations of NR n-type InAs mirror with plasmonic gratings are ongoing and results will be presented on the conference.

References
Enhanced Plant Water Status Measurement using THz Time-Domain Spectroscopy

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INTRODUCTION: Plant water status can be used as a reliable indicator for irrigation schedule to improve water use in agriculture. For this purpose non-destructive monitoring of leaf/plant water content has gained major interest. Recently, several studies demonstrated the potential of THz Time-Domain Spectroscopy (TDS) for non-destructive leaf-water measurements [1-2]. In these studies, leaf modeling used for data analysis considered a single heterogeneous layer made up of water, air, and dried tissue. Most of these studies focused on the plant response to severe drought. In this work, we focus on mild water stress for physiological leaf water contents which range between full turgor and turgor loss point. In addition, we take a closer look at the physical modeling of the leaf by using a more realistic multilayers approach.

RESULTS: Experiments were performed on Ivy leaves (Hedera helix). Gravimetric and THz measurements were carried out simultaneously on a single leaf disc dehydrating in the ambient atmosphere. Before measurements, leaf discs were enclosed in closed petri dishes with humidified filter paper in darkness at 5 °C for 12-24 h to allow full rehydration of leaf tissue. The THz measurements were carried out using a fiber-coupled THz TDS system in transmission mode employing a collimated beam. The THz and gravimetric measurements were done at the sampling rate of 15 Hz and 5 Hz, respectively. The RWC, that expresses the water content at a given time as relative to its fully turgid state, was calculated using equation 1 as:

\[ \text{RWC} = \frac{W_t - W_{dry}}{W_{sat} - W_{dry}} \times 100 \quad (1) \]

where \( W_t \), is weight measured at given time and \( W_{dry} \) and \( W_{sat} \) are weights in dried and water saturated states respectively. The initial disc weight \( W_{dry} \) is used as \( W_{sat} \) which corresponds to full turgor. To determine \( W_{dry} \), disc was oven dried at 75 °C for 24 h after measurements.

Fig. 1 (a) represents the transmission at a frequency of 200 GHz as a function of dehydration time. The results showed a clear increase in transmission as the leaves loosened water, which demonstrates the high sensitivity of THz approach even at high water content. In Fig.1 (b), we compare the RWC derived from the gravimetric and THz measurements. The leaf model used in this example is a simple heterogeneous layer made up of water, air, and dried leaf tissue. We note a significant deviation between the two methods, the relative error is up to 5%, which prevents a reliable evaluation of leaf water content from THz measurement.

Typical leaf anatomy [3] shows that distinct tissue layers compose the leaf and makes it a complex medium. We approximated the leaf by a multilayer model composed of distinct layers mimicking the different tissues. Based on typical volume density of the layers in terms of water, air, and dried tissue, we synthesized transmitted signals through a leaf. A dedicated root finding algorithm applied to the same virtual leaf but considering one layer model led to residual errors in RWC estimation similar to those using experimental data. In order to improve the water content estimate especially at high RWC a refined model of the leaf was therefore mandatory. More statistical analysis of the root finding algorithm for the inverse problem extraction process with refined models is currently ongoing. Future work will include experimental validation.

SUMMARY: We re-evaluate estimation of leaf water content using THz Time-Domain Spectroscopy. Using numerical simulations based on a realistic multilayer leaf model we show that the limitations of the one heterogeneous layer model and suggest new experimental strategy to overcome them.

REFERENCES

Probing Living Cells by THz Attenuated Total Reflection. Application to Quantitative Permeabilization Measurement

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Reversible permeabilization of live cells is a complex and increasingly addressed issue, whether it is for medical application, or in lab research protocols where a constant effort is made to reach more realistic investigation conditions in biological systems. It is characterized by increased molecule transfer through the cell membrane. Applications cover anticancer drugs or imaging markers delivery, gene therapy, etc. Reversible permeabilization is mostly obtained by techniques creating pores into the membrane, the most commons being electroporation, non-ionic detergents and pore-forming toxins [1-2].

The terahertz region has been shown to have potential in biomedical applications, but strong experimental limitations had long kept the study of biological objects down to the single purified molecule, simplified and/or pre-treated biological structures. Recent works demonstrated the possibility to spectroscopically address more complex systems, as cells and even accessible tissues or small organs [3-6].

A 10-µm-thick layer of epithelial MDCK cells was grown on a high resistivity silicon window, and then put on top of a silicon ATR prism [5]. An evanescent field resulting from internal reflection occurs at the surface of the window, probing an approximate thickness of 20 µm in the biological medium. No staining nor any sample preparation are needed in this non-invasive imaging device.

Fig.1. Normalized extracellular protein concentration and normalized THz contrast.

Half of the cell layer was kept untouched, and the other half was scratched free as a reference $S_{ref}$ for the terahertz signal $S$ originating from the cell layer. Displacement of the patch provides images of the cell layer, as well as the terahertz contrast defined by $\Delta = \left( S - S_{ref} \right) / \left( S - S_{ref} \right)_{t=0}$. At time $t = 0$, saponin (a non-ionic detergent) was added, creating reversible non-specific pores in the cell membrane [2]. We found a very good correlation between the decrease of $\Delta$ during permeabilization and the increase of extracellular protein content [7] (using a classical BCA [8]), as shown in Fig.1. A model mixing a broad experimental screening of various protein solutions, fitted by a theoretical approach, has been developed, linking $\Delta$ to proteins molecular weight and concentration.

A first example of permeabilization dynamics study is shown in Fig. 2, for two close saponin concentrations. Such dynamics are in agreement with the few existing studies, but had never been reported with this precision level nor with a non-invasive scheme. Comparison with usual permeabilization quantification methods will be discussed.

Fig. 2. $\Delta$ variation for 2 different saponin concentrations at $t=0$ min [50 µg/ml (●) and 75 µg/ml (●)].

References
Out-of-equilibrium proteins dynamic probed by THz spectroscopy: towards Frohlich’s condensation

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Bownian diffusion of freely moving biomolecules is usually considered to drive the dynamics of the molecular machinery maintaining cellular functions and thus Life. However, the high efficiency and rapidity of the encounters between cognate partners of biochemical reactions inside living cells calls for a more convincing explanation with respect to purely thermal-fluctuations-driven random walks. It has been surmised that a suitable interplay between Brownian diffusion and selective electrodynamics interactions acting at a long distance (up to thousands of Angstroms) could significantly accelerate the encounter times of interacting biomolecules in living matter [1, 2]. Up to now, no experimental evidence indicates that these collective vibrations, that should lie in the THz-frequency range, are sufficiently intense to activate some interactions between biomolecules. However, since these collective molecular oscillations are accompanied by the creation of a large dipole moment entailing the activation of electrodynamics long-range interactions [3], teraHertz-spectroscopy should see a change in absorption coefficient, even in aqueous medium.

In this communication we will experimentally show that model-proteins put out-of-equilibrium by an external excitation present a resonance that appears at a frequency in agreement theoretical prediction of Froehlich condensation model [4]. This resonance is interpreted, by the help of numerical support, as the signature of a large dipole moment possibly entailing the activation of electrodynamic long-range interactions between BSA-proteins in normal cytoplasm conditions [5].

References
Program

14H30 : Social program and free time including a museum visit or sailing (subject to weather conditions)

18H30 : Franco - Russian working meeting

19H30 : Gala Dinner
**Program**

8H30 : Welcome

9H00 : Session 9 - Solid Spectroscopy

*Chairman : J. Torres*

9H00 : Th1 - M. Huber  
«Ultrafast nanoscopy of plasmons in nanowires and heterostructures»

9H30 : Th2 - F. Teppe  
«Terahertz and Mid-Infrared studies of pseudo-relativistic fermions in HgCdTe heterostructures»

9H45 : Th3 - W. Knap  
«THz emission from Dirac-like fermions in bulk HgCdTe alloys»

10H00 : Th4 - H. Roskos  
«Time-Resolved Optical-Pump/Terahertz-Probe Spectroscopy of the Charge-Density-Wave Phase Modes in Blue Bronze»

10H15 : Th5 - J-Y. Chauleau  
«Imaging antiferromagnetic domains: Towards teraHertz manipulation»

10H30 : *** Coffee break ***
Ultrafast nanoscopy of plasmons in nanowires and heterostructures

M. A. Huber\textsuperscript{1}, F. Mooshammer\textsuperscript{1}, M. Plankl\textsuperscript{1}, L. Viti\textsuperscript{2}, F. Sandner\textsuperscript{1}, L. Z. Kastner\textsuperscript{1}, T. Frank\textsuperscript{1}, J. Fabian\textsuperscript{1}, M. S. Vitiello\textsuperscript{2}, T. L. Cocker\textsuperscript{1} and R. Huber\textsuperscript{1}

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The spatial resolution of far-field THz studies is intrinsically limited to the scale of the probing wavelength by diffraction. Apertureless scattering-type scanning near-field optical microscopy (s-SNOM) bypasses this limit by probing the THz near fields scattered from the apex of a sharp metal tip [1]. We use ultrafast multi-THz s-SNOM [2,3] to probe the transient, nanoscale dielectric functions of materials following photoexcitation by femtosecond near-infrared pulses (Fig. 1a). We have applied the system to trace the plasmonic response in a single InAs nanowire, showing that ultrafast near-field tomography reveals the < 50 fs build-up of a depletion layer at the wire’s surface. We have also resolved the oscillating electric near field on the surface of the nanowire directly in the time domain with 10 fs temporal resolution and 10 nm spatial resolution [2]. Additionally, by evaluating the spatial contrast of the pump-probe response in a single VO\textsubscript{2} nanobeam, we have shown that its insulator-to-metal phase-switching behaviour can be predicted [4]. Finally, we have designed and fabricated custom-tailored SiO\textsubscript{2}/black phosphorus/SiO\textsubscript{2} heterostructures and measured photo-activated surface phonon-plasmon polaritons with ultrafast pump-probe nanoscopy (Fig. 1b) and nano-spectroscopy. Due to its fast switch-on time (~50 fs) and well-defined energy and momentum [5], the transient polaritonic mode is a prime candidate for ultrafast control in future plasmonic devices.

Fig.1. Scattering-type scanning near-field optical microscopy (s-SNOM) of a black phosphorus(BP)/SiO\textsubscript{2} heterostructure. a) Schematic of ultrafast s-SNOM using multi-THz (mid-infrared, MIR) probe pulses and near-infrared (NIR) pump pulses on a SiO\textsubscript{2}/BP/SiO\textsubscript{2}/Si heterostructure. b) Comparison of the scattered MIR near-field intensity of the unexcited (top) and excited sample (bottom) reveals a standing wave pattern, which stems from a photo-activated surface phonon-plasmon polariton in the structure. All scale bars are 2 µm long.

References
Terahertz and Mid-Infrared studies of pseudo-relativistic fermions in HgCdTe heterostructures

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Bulk films and heterostructures based on HgCdTe compounds can be engineered to fabricate “gapped-at-will” structures. Therefore, 1D \cite{1}, 2D \cite{2} and even 3D \cite{3} massless particles can be observed in topological phase transitions driven by intrinsic (quantum well thickness, Cd content) and external (magnetic field, temperature or pressure) physical parameters. So far, the phases of 2D \cite{1} and 3D \cite{4} topological insulator have already been experimentally demonstrated in HgCdTe-based heterostructures. More recently, clear experimental evidence of the existence of 3D electronic states with conical-like spectrum was obtained in HgCdTe bulk films at specific Cd content \cite{3}. These 3D massless particles, called Kane fermions, have unique symmetry properties, which are not equivalent to any well-known case of massless particles in the relativistic limit of the quantum electrodynamics.

In this work, we report on our experimental results obtained by Terahertz (THz) and Mid-Infrared magneto-spectroscopy, on topological phase transitions driven by temperature in HgCdTe-based QWs \cite{5} and bulk films \cite{6}. These transitions are accompanied with the appearance of 2D and 3D massless electrons called Dirac and Kane fermions, respectively. We will also present first results on our investigation of 3D topological insulators surface states.

References

\begin{itemize}
\end{itemize}
THz emission from Dirac-like fermions in bulk HgCdTe alloys

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Effect of carriers heating and terahertz (THz)/Far infrared (FIR) magnetically tunable emission were subject of intense studies for decades [1, 2]. Impressive results have been obtained using GaAs and InSb semiconductors leading to the design of cyclotron resonance (CR) emitters based THz/FIR spectrometers [3]. Recent emergence of extremely high crystalline quality MBE grown HgCdTe alloys with extremely narrow band gap and even Dirac-like linear energy spectra rises questions about band structure related modification of electron heating and hope for THz cyclotron emission of high efficiency and tunability [4]. Indeed, decrease of the band gap and the cyclotron mass may lead to magnetic field tunability, greater by an order of magnitude than the one in GaAs or InSb semiconductors and non-equidistant Landau Levels (LLs) may help in decreasing of the parasitic self-absorption phenomena.

In this work we present experimental results on magnetically tunable THz emission from several HgCdTe bulk layers with extremely narrow energy band gaps (below 50meV). The samples were ~3µm thick films, MBE grown on (013) semi-insulating GaAs substrate covered by thick CdTe buffer. Our 4.2K cooled, background radiation shielded CR-THz spectrometer contained two independent 8 T and 14 T superconducting coils placed in the same cryostat. The sample, excited with electric field pulses was inserted into the first coil, while a magnetically tunable cyclotron resonance InSb-CR photoconductive detector was placed in the second one. We use this detector for spectral analysis of the emitted THz radiation. In Fig.1 we show a typical emission spectra for Hg₀.₈₁Cd₀.₁₉Te sample. One can clearly see CR emission lines moving to higher energies with increasing magnetic field. In Fig.1b a comparison between experimental and calculated transition energies is shown. Points are experimental results and two lines (for each alloy composition) correspond to calculated two lowest conduction band CR transitions –not resolved in the experiments. Transition energies were calculated using 8 band Kane Hamiltonian [5]. Nonlinear character of transition energies versus magnetic field increases with lowering Cd alloy composition showing transition from linear to square root behavior characteristic for Dirac-like band structure. A good agreement between theoretical curves and experimental results demonstrates that emission from our sample can indeed be attributed to the CR excitations in the conduction band. We have also performed preliminary experiments with lower energy bandgaps (going to zero) expecting higher tunability and efficiency of THz emission. Surprisingly we have observed decrease or complete absence of THz emission. Our results leads to discussion: if and how electric heating of electrons is modified when tuning the HgCdTe energy band structure towards Dirac-like one?

References
Time-Resolved Optical-Pump/Terahertz-Probe Spectroscopy of the Charge-Density-Wave Phase Modes in Blue Bronze

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Charge-density waves (CDW) are elementary excitations in low-dimensional organic/inorganic crystals spontaneously coupling conduction electrons and lattice. They manifest in a periodic charge-density modulation and the formation of an electronic gap at the Fermi edge [1]. Besides excitation across this gap (which typically occurs in the mid-IR), the CDW possess low-lying modes [2], which usually separate into a Raman-active amplitude- and an IR-active phase-channel. The latter appear as “phase-phonon” bands (including a low-energy “phason” near \( \omega = 0 \) [3]) in THz conductivity spectra. While the amplitude-phonons have been studied by others via Raman probing [4], we investigate the phase-phonons via their non-equilibrium response after pulsed optical excitation for the case of the prototypical quasi-1D CDW system blue bronze (K₀.₃MoO₃).

![Fig. 1. An example of a pump-induced differential THz field \( \Delta E(t, \tau = 0) \) for \( T = 50 \) K (\( h\omega_{\text{ex}} = 1.6 \) eV, \( F_{\text{ex}} = 550 \) µJ/cm²) measured in reflection, with a detection bandwidth of 0.5-2.8 THz. From 2D maps of such data, we derive the transient complex conductivity \( \Delta \sigma(\omega, \tau) \) which reveals a photoinduced blue-shift of the phase-phonon bands and a dynamic broadening.]

From the transient THz response of the system (see Fig. 1) and a comparison with the response expected on the basis of the time-dependent Ginzburg-Landau framework (TDGL) previously introduced for the amplitude-phonons [4], we find that we can reproduce the data, if we generalize the TDGL model to account for screening effects and impurity interactions. It turns out that such interactions specifically affect the phase-channel, and remain nearly hidden if only the amplitude-channel is investigated. This can be understood qualitatively because the phase-modes involve the translation of the CDW condensate, hence are more directly related to the charge transport and should be more sensitive to effects such as impurities, intra- and inter-chain interactions. Moreover, a comparison of the predictions of the phenomenological TDGL and quantum-mechanical models [2] reveals qualitative differences. Further experimental studies of the phase-channel and theory development are required to reach a complete, unified description of CDW physics.

References
Imaging antiferromagnetic domains: Towards teraHertz manipulation

J.-Y. Chauleau1,3, E. Haltz1, S. Fusil2, C. Carretero2, J.-B. Brubach3, P. Roy3, N. Jaouen3 and M. Viret1
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Antiferromagnets (AF) are currently in the limelight thanks to recent breakthroughs demonstrating the efficient effect of spin currents in interacting with the AF order parameter [1,2]. So far, due to the lack of net magnetization, controlling AF distributions has been rather challenging. Current-induced AF control also opens new perspectives in Terahertz magnetization dynamics. On the materials side, antiferromagnets represent the large majority of magnetic materials. Some of them show several simultaneous ordered phases and are commonly called ‘multiferroics’. As a result, when the AF order is coupled to a net polarization, it may be controlled by applying a voltage. Generally speaking, multiferroic materials [3] are the focus of an intense research effort due to the significant technological interest of multifunctional materials as well as the rich fundamental physics lying in the coupling of various order parameters. Among all multiferroics, BiFeO3 (BFO) is a material of choice because its two ordering temperatures (ferroelectric FE and AF) are well above room temperature. In addition a large magnetoelectric coupling has been demonstrated in single crystals as well as in thin films. Second harmonic generation has proven to be a powerful and elegant way to assess complex multiferroïc textures and to unentangle the different contributions at play [4]. In this presentation, we will first discuss the terahertz properties of AF order and we will present a study demonstrating the possibility to use second harmonic generation (SHG) to access the micron sized distribution of AF domain (Figure 1) in a multiferroic thin film. We will also show that they can also be efficiently manipulated by the internally optically rectified sub-picosecond electric fields. This opens the door to an all-optical terahertz control the AF order, independently of the electric polarization, but still using the magnetoelectric effect.

References
11H00 :  **Session 10 - Time Domain Techniques**  

*Chairman : A. Skhurinov*

11H00 :  Th6  -  M. Bernier  
«Optimized THz time-domain spectroscopy methods for a precise characterization of absorbent and scattering samples»

11H30 :  Th7  -  S. Dhillon  
«Short THz pulse generation from a dispersion compensated modelocked semiconductor laser»

11H45 :  Th8  -  M. Brossard  
«Direct measurement of terahertz wavefront pulses using 2D electro-optic imaging»

12H00 :  Th9  -  S. Bielawski  
«Photonic time-stretch: A technique for single-shot acquisition of THz signals at high repetition rate and high sensitivity»

12H15 :  Th10  -  V. Juvé  
«Giant polarization rotation induced by THz ultrashort pulses»

12H30 :  Th11  -  K. J. Kaltenecker  
«Ultra-broadband THz spectroscopy of molecular crystalline materials»

12H45 :  
***Final remarks***
Optimized THz time-domain spectroscopy methods for a precise characterization of absorbent and scattering samples

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Up to the end of the 80’s, the far infrared electromagnetic response of materials was investigated mostly thanks to the use of Fourier transform interferometers. In fact, Fourier transform infrared (FTIR) spectroscopy exhibits several advantages. During one scan, the recorded time-equivalent waveform is built from information delivered by the entire spectrum, while other dispersive prism or grating-based spectrometers receive at any time only signal from a narrow band, i.e. a rather smaller signal with a weaker signal-over-noise ratio (SNR). Secondly, and oppositely to dispersive spectrometers, the resolution of FTIR instruments is not limited by the size of the source. Nevertheless, FTIR instruments display some drawbacks mostly due to the lack of efficient sources and detectors of far infrared waves. The sources must be broadband in view of achieving narrow waveforms and thus broad spectral measurements. Generally, blackbody-like sources are implemented, like mercury lamps or globars. They are rather powerless and deliver incoherent light. Thus a long integration time is necessary to get a high SNR. Moreover, to obtain a high frequency resolution, the waveform must be recorded over a long equivalent time window, and noise is also recorded over this entire time window, even at times for which the effective signal is almost zero. Sensitive detectors, like Si bolometers, which operate at cryogenic temperatures, must be used. These problems, when dealing with FTIR experiments, i.e. long recording times at cryogenic temperatures, were solved by D. Auston and K. P. Chueng in 1985, who introduced and demonstrated the new concept of coherent time-domain far-infrared spectroscopy, known today as terahertz time-domain spectroscopy (THz-TDS). This initial work was completed by researchers at IBM Corp., who definitively installed THz-TDS as a very competing tool to study the far infrared properties of materials and devices. Since these pioneering researches, a strong effort has been devoted by numerous laboratories worldwide to improve THz-TDS equipment’s and techniques. Today, several books describe this technology and commercial systems are available. THz-TDS permits typically to investigate the range 0.1-5 THz, but some recent systems allow one to reach the mid-infrared, i.e. frequencies larger than several tens of THz. Also, the time-domain technique makes possible to perform optical-pump and THz-probe time-resolved experiment, for example to study the carrier dynamics in semiconductor or the kinetics of photo-induced chemical reactions. Moreover, nonlinear THz effects can be observed, thanks to the huge THz peak power in THz-TDS systems fed by an amplified mode-locked laser.

In a word, as the THz-TDS systems and techniques are numerous, we must ask ourselves which ones lead to the best characterization of a given sample. Since the extraction accuracies of optical parameters depends a lot on the intrinsic performances of the THz-TDS system (noise sources), and the experimental configurations (transmission or reflection), we give here the key rules the experimenter has to keep in mind to chose the most adapted THz-TDS technique for a given sample. We address the cases of samples presenting low-transmission bands (absorption lines or electromagnetic modes), and constituted of heterogeneous materials that scatter the impinging THz beam (powders, pellets…). If both reflection and transmission configuration are available in the laboratory, we will show how to combine both measurements to ensure precise extraction of the optical parameters of absorbent materials even in the absorption bands. In absence of reflection (or transmission) measurements, we will explain how to combine transmission (or reflection) THz-TDS measurements with Kramers-Kronig relations to achieve a trustful extraction.
Short THz pulse generation from a dispersion compensated modelocked semiconductor laser

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Dispersion compensation is vital for the generation of ultrashort and single cycle pulses from modelocked lasers across the electromagnetic spectrum. It is typically based on addition of an extra dispersive element to the laser cavity that introduces a chromatic dispersion opposite to that of the gain medium. To date, however, no such scheme have been successfully applied to terahertz (THz) quantum cascade lasers (QCL) for short and stable pulse generation in the THz range. In this work, we will summarize the current state-of-the art [1–3] and show a new monolithic on-chip compensation scheme (fig. a) for a modelocked QCL, permitting THz pulses to be considerably shortened from 16ps to 4ps (fig. b). This is based on the realization of a small coupled cavity resonator that acts as an ‘off resonance’ Gires-Tournois interferometer (GTI), permitting large THz spectral bandwidths to be compensated. This novel application of a GTI opens up a direct and simple route to sub-picosecond and single cycle pulses in the THz range from a compact semiconductor source.

(a)

(b)

Fig a) GTI schematic a) Schematic of the GTI coupled to a QCL to realised ultrashort THz pulses. The inset represents the GTI with asymmetric reflectivities, \( r_1 \) and \( r_2 \) and a cavity length, \( l \). b) Short Pulse generation from THz QCLs. Comparison of a QCL with a GTI (red) and a standard QCL cavity (black).

References
Direct measurement of terahertz wavefront pulses using 2D electro-optic imaging

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Wavefront characterization of terahertz (THz) pulses is essential to optimize far-field intensity distribution or spot focalization, as well as increase the peak power of intense terahertz sources. In the visible spectral region, Hartmann masks, invented a century ago, are used to perform optical metrology for a wide variety of applications [1]. However, in THz spectral range, it is well-known that spatiotemporal profiles of THz transient fields can also be directly determined through electro-optic (EO) sampling in a nonlinear crystal [2]. In this communication we will show that this latter technique is well adapted for the quantitative determination of the optical aberrations of THz pulses.

THz pulses are generated by optical rectification of amplified femtosecond laser pulses (800 nm, 1 mJ, 150 fs) in a ZnTe crystal. After beam expansion and collimation, the THz beam is sent into a second ZnTe crystal for electro-optic detection with a time-delayed laser probe pulse (Fig. 1a). There, the spatial distribution of the broadband (0.1–3 THz) THz electric field is converted into optical intensities captured by a CMOS camera. By varying the time delay between the probe and THz pulses, EO sampling can record the spatial dependence of the full (amplitude and phase) THz electric field in the crystal plane. Then, after Fourier transformation of the temporal data, we can get for every frequency the amplitude and the phase of $E_{\text{THz}}$ in this plane. From this phase mapping, it is possible to calculate the surface of equi-phase, which constitutes the definition of the wavefront.

To illustrate our method, we measured the optical aberrations of the THz beam presented in Fig. 1a, which is supposed to have a planar wavefront. The result is presented in Fig. 1b at 1 THz but can be perform at every other frequency within the broadband THz pulses. Clearly, this wavefront is not fully planar, some optical deformations are visible near the edge of the beam. This is clearer after the decomposition of the wavefront onto Zernike polynomials, where each polynomial represents a specific optical aberration. As shown in Fig. 1c, the THz wavefront presents some X and Y tilts associated with astigmatism that may be attributed to imperfect beam collimation or optical aberrations on the incident laser beam or the ZnTe nonlinear crystal. More generally, we believe that our THz wavefront sensor could provide a real advance for time-domain (imaging) spectrometers which require a perfect focalization of the THz beam or any other THz devices sensitive to wavefront distortions. Associated with deformable mirrors, it could open the route to THz adaptive optics.

**Fig. 1.** (a) Experimental setup. (b) Reconstructed THz wavefront at 1 THz. (c) Amplitude of the Zernike polynomials.

References
Photonic time-stretch: A technique for single-shot acquisition of THz signals at high repetition rate and high sensitivity

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We present a strategy that enables THz signals to be recorded in single-shot, and high repetition rate. This work has been motivated by the needs to monitor THz radiation pulse shapes and electron bunch shapes in accelerator facilities. The principle consists to imprint the THz pulses to be investigated onto the shape of laser pulses (i.e., performing Electro-Optic Sampling, EOS [1]), and then to stretch the laser pulses in time, up to the nanosecond range, using a long fiber (i.e., performing photonic time stretch [2]). The resulting laser pulses are “replica” of the THz pulse, that are magnified in time, and can be straightforwardly recorded using a single photodetector and an oscilloscope.

We present recent developments of this technique, with the objective to achieve high acquisition rates (up to 88 Mega traces/s) and/or high sensitivity (few V/cm). We also present recent results concerning measurements of THz coherent synchrotron radiation at Synchrotron SOLEIL [3,4,5].

References
Giant polarization rotation induced by THz ultrashort pulses

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Ultrashort single cycle THz pulses are found to induce a giant polarization rotation for visible light in LiNbO₃ crystal. Under specific conditions, the THz propagation through the LiNbO₃ crystal leads to efficient modulation of the polarization state of femtosecond optical probe pulses in time-resolved experiments. This time-dependent electro-optical polarization modulation is governed by $\chi^{(2)}$-type interactions between optical and THz electromagnetic pulses and occurs in the bulk of the crystal. In our experiments we use a Ti:Sa laser to generate intense THz pulses by means of the tilted-front pulse method in a MgO-doped LiNbO₃ crystal [1]. The emitted THz pulses are collected and focused into the sample (1 mm thick Z-cut undoped LiNbO₃). The THz pump pulse and a time-delayed femtosecond probe pulse interact together inside the sample and the probe's polarization rotation is followed in time with a polarization sensitive detection scheme as shown in Fig. 1.a). Fig. 1.b) shows a typical signal obtained at a probe incidence internal angle of 9°, with different modulation frequencies appearing. Fig. 1.c) shows that, for different angles between THz and probe, different frequencies of modulation can be obtained up to roughly 1.6 THz. The experimentally measured maximum angle of polarization rotation of 6° is large compared to other studies [2], and represents a new pathway for controlling the polarization state of light at ultrafast time scales.

![Fig.1.](image)

**Fig.1.** a) Schematic of the time-resolved Kerr rotation measurement in LiNbO₃. b) Intensity modulation resulting from probe’s polarization rotation as a function of the time delay between the THz pump pulse and the 400 nm probe pulse. c) The measured two frequencies as a function of the internal angle $\theta_{\text{inc}}$. The dashed lines are results of model calculations.

References
Ultra-broadband THz spectroscopy of molecular crystalline materials

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Ultra-broadband THz time-domain spectroscopy (THz TDS) systems based THz air-photonics provide the possibility to generate and detect ultra-short single-cycle THz pulses. This allows to coherently measure the optical properties of materials in a significantly extended frequency range, which is an order of magnitude larger than the bandwidth of traditional THz TDS systems based on nonlinear crystals or photoconductive switches.

In this work, we use ultra-broadband THz time-domain spectroscopy measurements based on two-color laser induced plasma THz generation and air biased coherent detection (ABCD) to investigate the optical properties of molecular crystalline materials in the frequency range from 0.3 THz to 40 THz and beyond \cite{1,2,3}. We measured the transmission properties of different molecular crystalline materials pressed into polyethylene (PE) pellets (mass ratio 1:9). For comparison, we performed FTIR measurements using a commercial system (Bruker Vertex V70).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Fig. 1. (a) Transmission spectrum of Ibuprofen obtained by ultra-broadband THz-TDS (blue) and FTIR (red) measurements. (b) Absorption spectrum of Ibuprofen calculated from the THz-TDS data.}
\end{figure}

Figure 1(a) shows the transmission spectrum of an Ibuprofen/PE pellet in the frequency range from 0 THz to 50 THz obtained by ultra-broadband THz TDS (blue) and FTIR (red). The transmission dips in the frequency window from 10 THz to 42 THz are well reproduced by both techniques, demonstrating the potential of ultra-broadband THz TDS to bridge the THz and IR frequency regime. Since the TDS approach is a coherent measurement technique, we also obtain phase information which allows to extract even more information on the dielectric properties of the sample. This is illustrated in Figure 1(b) showing the absorption spectrum of Ibuprofen.

In summary, we study the transmission properties of molecular crystalline materials like Ibuprofen by ultra-broadband THz TDS and compare the results to FTIR measurements.

References